1993 Project Abstract
For the period ending June 30, 1995
This Project was supported by the MN Future Resources Fund.

Title: Managing Agricultural Environments of North-Central Minnesota Sandy Soils
Program Manager: H. H. Cheng
Organizations: University of Minnesota and Minnesota Department of Agriculture
Legal Citation: M.L. 93, Ch. 172, Sec. 14, Subd. 3(h) Agriculture
Appropriation Amount: $480,000.

Statement of Objectives:

This project was designed to address water quality concerns arising from corn and potato production on sandy soils in north-central Minnesota by developing improved management strategies for water, nitrogen, and herbicide use. The project has the following objectives:

A. Evaluate current agricultural management practices in north-central Minnesota.
B. Refine diagnostic criteria to predict in-season nitrogen needs for irrigated potatoes.
C. Improve best management practices for irrigated potato and corn.
D. Evaluate herbicide losses to groundwater under irrigated potato production.
E. Develop computer models for BMPs that consider movement of water, nitrogen, and herbicides.
F. Disseminate information.

Overall Project Results:

A survey program: FANMAP (Farm Nutrient Management Assessment Program) was developed and used to assess actual farming practices in non-irrigated (58 farms covering 31,000 acres) and irrigated (24 farms covering 19,000 acres) crop production in the sandy regions of north-central Minnesota. The results showed that farmers were generally aware of the different nitrogen (N) sources for their crops and have attempted to voluntarily adopt strategies to reduce fertilizer N inputs by giving credits for manure and legumes. For improved management, they would need to have further understanding of the nature of the soils and climate specific to each farming area and management skills for proper amounts and timing of N inputs from various sources. Recommendations for N fertilizer use must take into account of previous history of manure applications and legume crops in rotation.

For irrigated potato production, diagnostic criteria for predicting in-season N needs for potato production were further refined, and a quick field test for nitrate in petiole sap was developed and calibrated. Approximate sap nitrate-N sufficiency ranges for Russet Burbank potatoes (the predominant variety grown in Minnesota) are 1300-1600 ppm for initial vegetative growth and tuber initiation; 900-1200 ppm for tuber growth and bulking; and 550-800 ppm for tuber bulking and maturation. Calibration studies should be conducted for other varieties.

To monitor nitrate and herbicide loss through leaching under potato production in irrigated fields, both water movement and nitrate and herbicides in leachates were periodically measured. Over the growing season, more water was lost by leaching under the furrow than under the row. However, water loss cannot be equated to nitrate or herbicide leaching as N can be removed by volatilization and denitrification, or be tied up by the soil organic matter by immobilization. In fields with corn-potato rotations, use of turkey manure as N sources need to be monitored closely as in-season N mineralization from the manure and N needs for the two crops differ over the growing season. Similarly, herbicide management also depends upon the climatic conditions of the field influencing the degradation of the chemicals and upon the management of water inputs under irrigation.

Several studies were conducted to develop, test, and validate models for BMPs that consider movement of water and chemicals in soils. The SUBSTOR-Potato model was tested for potato growth and nitrate leaching under the conditions of north-central Minnesota. Although the model could simulate the general trends, its accuracy was less satisfactory as it failed to account for variable water infiltration in the field. A dye tracer experiment was carried out to evaluate the extent of preferential transport and the mechanisms responsible for initiating preferential flow paths. Preferential flow was more extensive under flooded conditions than under sprinkler irrigation.

For developing strategies to improve water management, a hydrologic water balance computer model was used to identify peak leaching periods and the corresponding percolation based on long-term daily meteorological data, using 31 years of actual data at several locations. Percolation losses are higher in soil with lower water holding capacities and during spring and fall because of less evapotranspiration from crops. Results of simulation from CERES-Maize model showed that using yield goals to select N application rates may not be appropriate because climate is a determinant of yield and the potential for nitrate leaching was not considered by this process. Field and simulation studies were conducted to evaluate the applicability of subsurface drip irrigation as an alternative for providing needed water for crop production.

Results showed that water movement under a ridge-furrow system is two-dimensional with little movement toward the upper part of the ridge. Shallower placement of drip lines led to incomplete root development, whereas deeper placement led to deep leaching and nutrient deficiency at early stages, if the line is also used for nutrient supply.

Since extreme climate variations can never be controlled, their probability of occurrence was calculated from historical climatic records at six locations within the north-central region. Guidelines were developed from these probability calculations to help management decisions on the risks involved in applying nutrients and herbicides during certain times of the growing season. Together with model-simulated scenarios on irrigation practices and crediting various N sources, guidelines can now be formulated for improving the current crop management practices so that risks for groundwater pollution can be further reduced while productivity of the fields can be maintained.

Project Results Use and Dissemination:

Five on-farm demonstrations on improved practices were conducted during the two-year project to show how timing of fertilizer applications and incorporation of manure in N management in different cropping systems can maintain high yields while reducing the risks of nitrate leaching. By working with producers throughout the duration of this project from survey of current practices; to conducting needed research to understand the critical factors in managing water, nitrogen, and herbicide use; to demonstration of improved best management practices for on-farm operations, we have developed a ready audience who are willing to participate in the improvement of their production practices. A number of research and extension publications will be resulting from this project to further enhance the adoption of these improved BMPs.

1993 3(h)

Managing Agricultural Environments of North-Central Minnesota Sandy Soils

Final Detailed Report Submitted to the
Legislative Commission on Minnesota Resources

Department of Soil, Water, and Climate
University of Minnesota

and

Minnesota Department of Agriculture

July 1, 1995

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Date of Report: July 1, 1995

LCMR Final Report - Detailed for Peer Review - Research

I. Project Title: Managing Agricultural Environments of North-Central Minnesota Sandy Soils

Program Manager: Dr. H.H. Cheng, Head
Soil Science Department
University of Minnesota
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Phone: (612) 625-9734 FAX (612) 625-2208

A. Legal Citation: M.L. 93 Chpt. 172, Sec. 14, Subd. 3(h) Agriculture

Total Biennial LCMR Budget: $480,000; Balance: $0

Appropriation Language as drafted 7/27/92: This appropriation is from the future resources fund to the commissioner of agriculture for a contract with the University of Minnesota to develop improved management strategies for water, nitrogen, and herbicide use on sandy soils in north-central Minnesota.

B. LMIC Compatible Data Language: not applicable
C. Status of Match Requirement: not applicable

II. Project Summary: This project will address water quality concerns arising from corn and potato production on sandy soils in north-central Minnesota by developing improved management strategies for water, nitrogen, and herbicide use. Crop production on sandy soils is believed to have led to increased nitrate and herbicides in the groundwater of north-central Minnesota. On the other hand, crop production, especially potato production, is extremely important to the economy of the region. The primary goal is to help provide improved nitrogen and herbicide management options for farmers that maintain profitability but reduce the potential for contamination of groundwater from nitrate and herbicides from agricultural sources. This will be accomplished through research and education in north-central Minnesota.

III. Statement of Objectives:
A) Evaluate current agricultural management practices in north-central Minnesota; B) Refine diagnostic criteria to predict in-season nitrogen needs for irrigated potatoes; C) Improve best management practices for irrigated potatoes and corn; D) Evaluate herbicide losses to groundwater under irrigated potato production; E) Develop computer models for BMPs that consider movement of water nitrogen, and herbicides; F) Disseminate Information.

IV. Research Objectives

A. Title of objective: Evaluate current agricultural management practices in north-central Minnesota.

A.1. Activity: Grower survey for information on irrigation amounts and timing, fertilizer types and rates, soils test values, yields and yield goal setting, pesticide types and application rates, crop rotations, tillage practices, manure rates and application times, and nitrogen credits for alfalfa and manure sources.

A.1.a. Context within project: Currently there is a shortage of information on how farmers manage agricultural chemicals, organic nitrogen sources (manures, legumes), and water (such as irrigation amounts and timing) which have direct effects on water quality. Obtaining this type of information is critical on the coarse-textured soils, particularly under irrigated specialty crops (such as potatoes and edible beans) and corn. This inventory will supply real time data inputs for models that can estimate leaching losses as well as aid in identifying or further refining best management practices. Approximately 40% of the state's potato production acres (70,000-80,000 acres statewide on an annual basis), are grown in the irrigated coarse-textured soils. Potato producers representing three geomorphic regions will be interviewed. These regions, which account for approximately 60% of the state's irrigated potato acreage, are: the Detroit Lakes Pitted Outwash Plain; the Park Rapids-Staples Outwash Plain; and the Mississippi Valley Outwash.

A.1.b. Methods: Less than 20 producers account for a high percentage of the potato acreage in these three regions. All potato producers in these particular geographic locations will be requested to participate in the inventory process. Growers will be requested to provide information on irrigation amounts and timing, fertilizer types and rates, soil testing, yields and yield goal setting, pesticide types and rates, crop rotations, tillage practices, manure rates and application times, and nitrogen credits for alfalfa and manure sources. In cooperation with the Minnesota Irrigators Association and Minnesota Extension Agents, growers will be interviewed through a one-on-one type process. This is the only feasible method for collecting information on such a high level of detail.

In a recent LCMR project, nitrogen use and current management strategies were identified for corn, edible beans, and alfalfa cropping systems which focused specifically on irrigators in the Detroit Lakes Pitted Outwash Plain and the Park Rapids-Staples Outwash Plain. In order to fully understand the dynamics of nitrogen cycling on the coarse-textured soils in these regions, information will also be needed for dryland agriculture, thus, a survey or farm inventory assessment effort will be designed to focus on dryland agriculture. Contributions can be significant under non-irrigated conditions if nitrogen "best management practices" are not followed and losses can be substantial following water-limiting cropping seasons. One-on-one interviews as previously described or extensive mail out surveys will be the tools selected to accomplish this assessment. Spatial sampling methodology, as described by Nowak and O'Keefe (USDA Progress report No. 1, April, 1991) will be tested for possible implementation for the non-irrigated farm assessments.

A.1.c. Materials: Questionnaires and Extension bulletins
A.1.d Budget: $25,000, **Balance:** $0
A.1.e Timeline:

	7/93	1/94	6/94	1/95	6/95
Irrigated Potato Inventory					
Design inventory questions/forms	xx				
Data base programming		xx			
Establish sampling populations			xx		
One-on-one interviews				xx	
Summary, publications of results				xx	
Nonirrigated Agricultural Survey					
Design inventory questions/forms	xx				
Data base programming		xx			
Establish sampling population			xx		
One-on-one interviews/mailouts			xx		
Summary, publication of results				xx	

A.1.f. Status: Current Nutrient Management Practices on Non-Irrigated Central Sands. Fifty-eight farms, covering over 31,000 acres, participated in the **FA**rm **N**utrient **M**anagement **A**ssessment **P**rogram (**FANMAP**) with staff from the Minnesota Department of Agriculture. Producers volunteered 2-4 hours of their time to share information about their farming operation. Producers were carefully selected to represent a wide diversity of management skills and farm characteristics. The overall purpose of the program was to develop a clear understanding of current farm practices regarding agricultural nutrients and utilize this knowledge for future water quality educational programs.

Nitrogen management on the Central Sands is challenging due to the nature of the soils and additional management skills required to manage organic N inputs. Manure accounts for approximately 33% of the 'first year available' N; legumes account for another 17%. Obviously proper crediting of both of these sources is needed to successfully manage N on these outwash sands. Yield goals varied tremendously on these outwash soils due to the wide range of organic matter content and available moisture holding capacity. The overall corn yield goals were 70 bu/A. Consequently, the nutrient inputs in general were significantly lower than most other regions of the state.

On corn acres where no previous manure or legume credits existed to confound the rate selection process, producers appear to be in excellent agreement with recommendations that were made by UM/MES. Corn acres which were above or below the UM recommendations were equally distributed.

Overall, producers reduced N fertilizer inputs following "first year" alfalfa by 17 lb/A. However, additional reductions (20-30 lb/A) could be made with a low probability of yield loss. One of the difficulties in the data collection process was obtaining reliable alfalfa information prior to stand termination. It appears that producers need the assessment tools for determining alfalfa stand densities and record keeping systems to aid in more effectively capturing alfalfa credits.

Producers were basically reducing commercial N inputs by 24 lb/A in scenarios where previous manure applications were made to non-legume crops such as corn. Producers were under-estimating the value of the manure by approximately 25 lb/A. It is a common practice to apply manure to old alfalfa stands which are followed by corn in the rotation. In this scenario, producers were found to reduce their commercial inputs by approximately 17 lb/A. However the combination of alfalfa and manure credits, coupled with the fertilizer (average of 40 lb/A), resulted in over-applications of 70 lb/A. In these situations, only a starter N application should be applied and would trim 20 to 30 lb/N/A from the N budget. Due to the low yield potentials of these soils, all the N requirements for corn will be supplied from alfalfa stands of 2 plants/ft or denser. Producers could capture a higher percentage of the "fertilizer replacement value" by applying the manure into other corn rotations. Approximately 50% of the corn acres did not receive any manure application so there is ample locations to apply the manure. From a water quality perspective, the most significant impacts could be made by improving the N crediting process in this particular cropping scenario.

Proper timing of N applications is one of the key management strategies that producers in this region can implement to minimize N leaching losses. Producers have been encouraged to avoid fall application on any coarse-textured soils. FANMAP determined that fall application of N was extremely rare; spring preplant and starter N accounted for 56% of applied N fertilizer with the remaining balance sidedressed. Timing and source selection of N fertilizers appeared to be in excellent agreement with current BMPs developed by MES in conjunction with MDA. A very high percentage of the N fertilizers were ammonium based products.

This area has a high diversity of storage/collection systems, most of which provide some opportunity for storage. The process of manure crediting is greatly simplified with manure storage systems that allow for a minimal number of land application events. Over 80% of the N retained after storage originated from a variety of systems that allowed for some storage benefits. In previously studies by the MN Extension Service, the nutrient value from manure has been found to be highly variable. Manure testing needs continual promotion as a fundamental part of a nutrient management plan. Only 10% of the producers had tested their manure previously to this project.

There were some very positive findings from this study. There is strong evidence that producers are voluntarily adopting the educational materials and strategies developed by the University of Minnesota/MN Extension Service. It is also evident that promotional activities need to continue and be specifically targeted to deliver the most recent technology and recommendations. Strong similarities exist in all existing FANMAP projects: producers are generally managing commercial N inputs successfully (although frequently using outdated recommendations) but continually under-estimate the N credits associated with manure and alfalfa inputs.

Current Nutrient Management Practices For Irrigated Potatoes on Sandy Soils. Twenty-four potato farmers covering over 19,000 acres, participated in the **FA**rm **N**utrient **M**anagement **A**ssessment **P**rogram (**FANMAP**) with staff from the Minnesota Department of Agriculture. Producers volunteered 2-4 hours of their time to share information about their farming operation. Producers were carefully selected to represent irrigated potatoes on sandy soils. The overall purpose of the program was to develop a clear understanding of current farm practices regarding agricultural nutrients and utilize this knowledge for future water quality educational programs.

Nitrogen management for potato growers on sandy soils is challenging due to the nature of the soils and additional management skills required to manage irrigation scheduling. The overall potato yield goals were 410 cwt/A and N inputs came primarily from commercial fertilizer. Only one grower had N contributed from manure and less than 5 lbs/A were contributed from previous legumes. Cover crops were used extensively for early and medium maturity potatoes; consistent with current BMPs.

Overall, producers were generally over applying N by 48 lbs/A according to recommendations from the U/M. In addition it appears potato growers could reduce their N rates in starter fertilizers by 35% from 67 lbs/A to the recommended 40 lbs/A according to U/M recommendations. Research on early maturing potatoes, especially the new varieties, will provide further assistance to potato growers. Proper timing of N applications is one of the key management strategies that producers in this region can implement to minimize N leaching losses. Producers have been encouraged to avoid fall application and research suggests this practice is being endorsed. Timing and source selection of N fertilizers appeared to be in excellent agreement with current BMPs developed by MES in conjunction with MDA. A very high percentage of the growers were using multiple split applications and N applications through fertigation were consistent with recommended practices also.

Soil testing was done on 68% of the potato acres providing information to assist the growers in correct fertilizer application amounts. In regard to Phosphorus, growers seem to be over applying by approximately 92 lbs/A according to U/M recommendations. Here again, research on additional varieties and early maturing potatoes will provide assistance to the potato growers.

There were some very positive findings from this study. There is strong evidence that producers are voluntarily adopting the educational materials and strategies developed by the University of Minnesota/MN Extension Service. It is also evident that promotional activities need to continue and be specifically targeted to deliver the most recent technology and recommendations.

A. Status:

General Information: Farms on Non-Irrigated Outwash Soils

County Educators (MN Extension Service) from Becker, Hubbard, Otter Tail, Todd, and Wadena counties were contacted and individually interviewed in October,1994. Purpose of the interviews was: to inform them of the specifics of the project and overall goals; obtain pertinent county information (i.e. locations of outwash sands); and potential candidates (farmers) and their agronomic management skills as perceived by the County Educator. County Educators also served as an important link between the farmers and the researchers; Educators commonly made personnel telephone calls to the potential participants after the introduction letter (Appendix A-1) was mailed. Part of the criteria for consideration was that the farms needed to be overlying outwash sands and that they were dominantly non-irrigated. Fifteen to twenty contacts, classified as either "Low", "Average" , or "High" management skills, were collected in each of the five counties. Introduction letters (Appendix A-1), signed by the Commissioner of Agriculture, were mailed out to the farmers in November, 1994. The letter's intent was to identify: the overall LCMR project; the purpose of the nutrient assessment; why they were selected; and what types of information and amount of their time would be necessary to successfully complete the project. A total of 76 letters were send and 58 (76%) producers went through the interview process.

Nutrient Management Data Collection: Farms on Non-Irrigated Outwash Soils

Inventory forms and data base design were patterned after a previous successful project[1]. A copy of the inventory form is included in Appendix A-1. Timing, rates, method of applications were collected for all nitrogen (N) and phosphate (P_2O_5) inputs (fertilizers, manures, and legumes) on **a field-by-field basis for all acres owned or rented**. There were 789 management areas in the entire study. A management area is defined as a field or group of fields (managed by the same producer) that had the same nutrient inputs. If an individual field was not managed uniformly, it would be broken down into separate management areas. Soil and manure testing results were also collected if available. Nutrient inputs and yields were specific for the 1994 cropping season. Crop types and manure applications (starting in the fall of 1993) were also collected from the 1993 season for purposes of 1994 nitrogen crediting. Long term yield data generally reflected the past 3 to 5 years. Livestock census and other specifics for the entire farm (i.e. types of manure storage systems, total farm sizes) were also recorded.

[1]Effective Nitrogen and Water Management for Water Quality Sensitive Regions of Minnesota, LCMR 1991-93

Farm Size and Crop Characteristics of the Selected Farms: Farms on Non-Irrigated Outwash Soils

Fifty-eight (58) farmers were interviewed during December, 1994 and January, 1995. Total inventoried acres by county (and number of farms per county) are as follows: Becker 4,235 (9); Hubbard 6,545 (13); Otter Tail 9,169 (13); Todd 5,729 (11); and Wadena 6,057 acres (12). Total area covered by the interviews was 31,735 acres; 18,902 acres were identified as tillable (Table A.1.-1). The average farm size was 541 acres with 320 acres in cropland. Thirty-two (32) of the farms were dominantly dairy. All the remaining farms had some type of livestock although the animal types were highly variable.

Table A.1.-1. General description of all farms participating in the 1994 Non-Irrigated Central Sands nutrient management survey.

		Total Acreage Inventoried			Average Acreage by Farm		
County	Farm	Total(1)	Crop(2)	Noncrop	Total(1)	Crop(2)	Noncrop
		..... Number of Acres					
Becker	9	4,235	2,377	1,858	470	264	206
Hubbard	13	6,545	3,261	3,284	504	251	253
Otter Tail	13	9,169	6,477	2,692	705	498	207
Todd	11	5,729	3,139	2,590	521	285	235
Wadena	12	6,057	3,648	2,409	505	304	201
Mean	**11.6**	**6,347**	**3,780**	**2,567**	**541**	**320**	**220**
Total	**58**	**31,735**	**18,902**	**12,833**	**2,705**	**1,602**	**1,102**
Percent Total		**100**	**59.6**	**40.4**			

(1) Includes owned, rented and rented out acres
(2) Includes fertilized or manured pasture and set-aside acre

Corn (31%), hay[2] (29%) and small grains (16%) accounted for over 76% of the cropland acres (Figure A.1.-1). Remaining acres were highly mixed. In contrast, the cropland distribution across <u>all farms in the five county area</u>[3] was dominated by corn (26%), hay (29%), soybeans (11%) and small grains (29%) (Figure A.1.-2). The selected farms were skewed towards more miscellaneous crops and less soybean and grain acres than the overall five county distribution. County specific data is given in Table A.1.-2.

[2] Defined as the sum of alfalfa and clover acreage.
[3]MN Agricultural Statistics 1994. National Agricultural Statistics Service, St. Paul, MN.

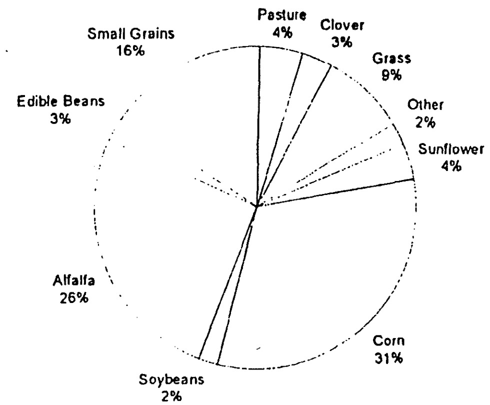

Figure A.1.-1. Crop type distribution across all cropland acres of the selected farms.

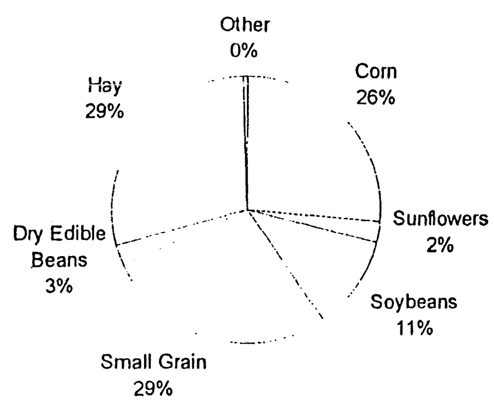

Figure A.1.-2: Crop type distribution across all cropland acres in Becker, Hubbard, Otter Tail, Todd, and Wadena Counties. Acreage based on 1993 statistics (MN Agricultural Statistics, 1994)

Table A.1.-2. Average distribution of cropland acres per farm by county - 1994

County	Corn	Alfalfa	Small Grains	Edible Beans	Sun-flower	Clover	Other	Total
	In Acres							
Becker	289	870	683	0	201	20	314	2377
Hubbard	600	761	547	265	208	10	870	3261
Otter Tail	2826	1462	1215	246	270	216	242	6477
Todd	1307	832	252	0	0	271	477	3139
Wadena	1005	1009	287	0	0	20	1327	3648
Mean	1205	987	597	102	136	107	646	3780
Total	6027	4934	2984	511	840	1671	3230	18902
Total By Percent	31.9	26.1	15.8	2.7	3.6	2.8	17.1	100.0

Commercial Fertilizer Use Characteristics on Selected Farms: Farms on Non-Irrigated Outwash Soils

Corn (61%) and small grains (20%) accounted for 81% of the total N commercial fertilizer use (Figure 3). Ninety-three percent (93%) of the total corn acreage and 68% of the small grains received commercial N fertilizer (Table A.1.-3). Average fertilizer N rate on corn acres was 53 lb/A; this rate is calculated as the means across all commercially fertilized corn acres regardless of past manure or legume N credits. Total N inputs will be discussed later in the "Nitrogen Balances and Economic Considerations" section. Alfalfa, small grains, and edible beans received 20, 50, and 70 lb/N/A, respectively (Table A.1.-3 and Figure A.1.-4). Phosphate rates ranged between 17 to 25 lb/A across the major crops (Table A.1.-3).

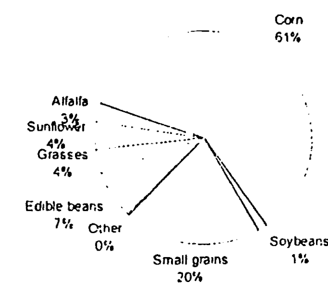

Figure A.1.-3. Distribution of commercial nitrogen fertilizer by crop type. Total nitrogen supplied by fertilizer was 496,000 pounds across all 58 farms.

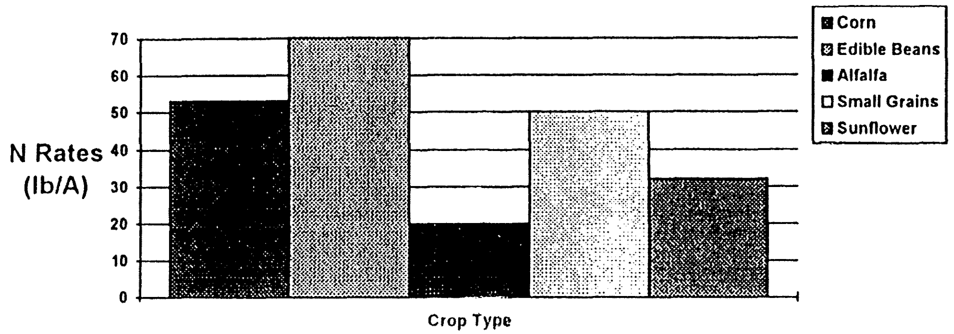

Figure A.1.-4. Average N fertilizer rates across fertilized acres by crop type.

Table A.1.-3. Distribution of commercial nitrogen and phosphate applications on cropland - 1994

Crop	Acres Receiving N Fertilizer	Total N Applied (LBS X 1000)	Acres Receiving Phosphate Fertilizer	Total Applied P_2O_5 (LBS X 1000)
Corn	5,621	298.1	5,263	92.2
Clover	16	0.8	16	0.1
Soybeans	158	6.9	0	0
Alfalfa	700	13.9	574	14.4
Small Grains	2,016	101.4	1,520	26.5
Edible Beans	511	35.6	246	4.3
Sunflower	626	20.3	596	12.4
Other	335	18.9	0	0.0
TOTALS	**9,985**	**496**	**8,215**	**150**

Timing of N fertilizer applications is an important consideration in maximizing fertilizer use efficiency and minimizing environmental effects. Due to the high probability of leaching in these coarse-textured soils, the overall strategy is to apply the N to closely match crop uptake. Best Management Practices (BMPs)[4] developed for this region of Minnesota focus on a number of timing issues. First, fall applied N is not recommended under any circumstances. In this study, there was no fall fertilization on corn (Figure A.1.-5) and less than 2% of all remaining N fertilizers used on non-corn crops was fall applied (Figure A.1.-6).

[4] M.A. Schmitt and G.W. Randall 1993. Best Management Practices for Nitrogen Use in East-Central and Central MN. . AG-FO-6129-B.

Secondly, "when soils have a high leaching potential, application of nitrogen is a sidedress or split application program is preferred"[5]. In this study, over half of the N is applied prior to corn emergence (Figure A.1.-5). Considering the low total rate of application (53 lb/A) and that recommended starter N rates are usually 10-20 lb/A, this distribution appears consistent with existing BMPs. The same conclusions are the same for all "non-corn" applications (Figure A.1.-6).

Another important BMP is to select the proper N source. In situations were the bulk of the N is applied in a single application, anhydrous ammonia or urea are highly recommended. These two forms of N account for only 19% of the total commercial use (Figure A.1.-7). Granulars[6] accounted for 81% of the applied commercial N. A high percentage of the granulars are ammonium based; negative environmental impacts from these types of products are probably minimal. Amounts of nitrate based products such as ammonium nitrate or UAN were very limited. The N source selections found in this study are vastly different than the results from irrigated agriculture in the same counties[7]. Generally anhydrous ammonia and urea account for 60-70% of the total N sales.

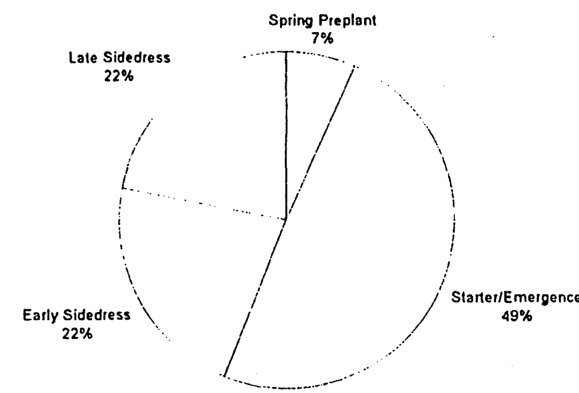

Figure A.1.-5. Timing of N fertilizer applications on corn acres. Overall mean N rate was 53 lb/A.

[5] M.A. Schmitt and G.W. Randall 1993. Best Management Practices for Nitrogen Use in East-Central and Central MN. . AG-FO-6129-B.
[6] Granular fertilizers represent a large array of various formulations, excluding urea, which are dominantly ammonium based.
[7] Effective Nitrogen and Water Management for Water Quality Sensitive Regions of Minnesota, LCMR 1991-93

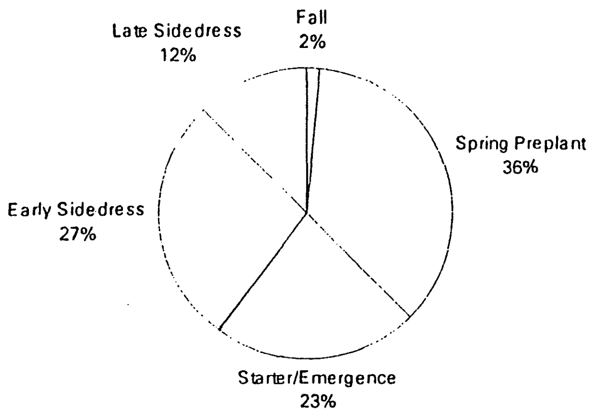

Figure A.1.-6. Timing of N fertilizer applications on all "non corn" acres. The overall mean N rate was 45 lb/A. Over half of the N on "non corn" acres was applied to small grains.

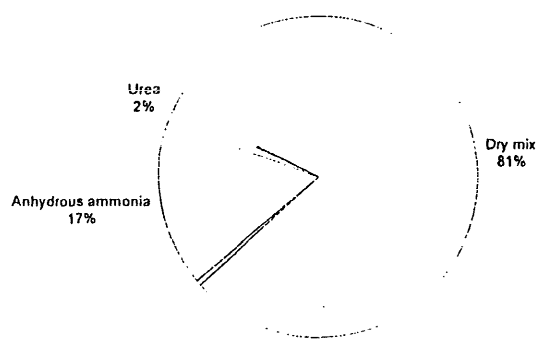

Figure A.1.-7. Contributions of N from various fertilizer sources on selected farms.

The use of nitrification inhibitors can be helpful in controlling either leaching losses (coarse-textured soils) or denitrification during periods of near-saturated conditions on the fine-textured soils. Inhibitor use is recommended on coarse-textured soils with early spring applications. Due to the low N rates used on these farms, the use of inhibitors would be cost prohibitive. Only one producer used an inhibitor on 120 acres of corn.

Livestock and Manure Characteristics of the Selected Farms: Farms on Non-Irrigated Outwash Soils

Factors directly affecting nutrient availability from land applied manure (including manure storage, types, manure amounts being generated, application methods, incorporation factors and rates) were also quantified to complete the "whole farm" nutrient balance. As previously mentioned, over half the farms were dairy and the remaining were a wide mix of animal types as indicated by Table A.1.-4. This table includes a complete animal inventory, including nitrogen and P_2O_5 produced[8] and collected.

Table A.1.-4. 1993 livestock numbers, and manure N and P_2O_5 produced and collected by livestock types in sample population.

Livestock Type	Livestock Number	Manure Nitrogen Produced	Manure Nitrogen Collected	Manure P_2O_5 Produced	P_2O_5 Collected
		Pounds X 1000		Pounds X 1000	
Dairy Cows	2,029	427.0	387.2	173.0	156.9
Calves & Heifers	2,143	210.8	132.8	84.5	53.0
Dairy Steers	331	45.8	38.8	18.6	15.8
Boars	32	1.0	0.9	0.8	0.7
Sows & Litters	638	18.8	18.8	14.7	14.7
Feeders (20 - 50 pounds)	10,163	1.0	1.0	0.3	0.3
Finishers (50 -240 pounds)	8,387	33.6	33.6	12.6	12.6
Bulls	64	11.9	2.8	8.8	2.0
Beef Cows & Calves *	1,369	211.8	59.5	161.0	45.2
Beef Feeders	237	38.2	22.0	27.6	15.9
Sheep Ewes	699	11.2	5.6	3.8	1.9
Feeder Lambs	1,125	9.0	3.8	3.2	1.3
Chickens	900	0.1	0.0	0.1	0.0
Turkeys	175,000	191.3	191.3	169.2	169.2
Horses	18	1.4	0.7	0.5	0.2
TOTAL		1,213	899	679	490

Estimated amounts of N and P_2O_5 **per farm** produced from all livestock were 21,000 and 12,000 pounds, respectively . Dairy cows, calves and heifers generated approximately half of the associated N (Figure 8) and P_2O_5 (Figure A.1.-9) produced through manure .

[8] Livestock Waste Facilities Handbook, Midwest Plan Services, Iowa State University, Ames, Iowa. 1985.

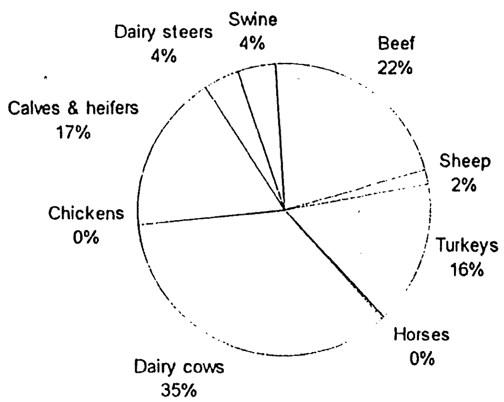

Figure A.1.-7. Amounts of nitrogen (total) generated by animal types across all selected farms. Total N produced was 21,000 pounds/farm.

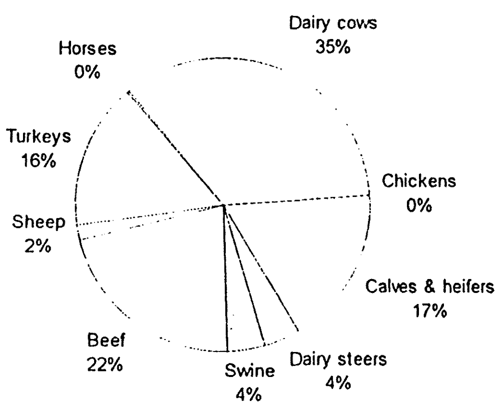

Figure A.1.-9. Amounts of P_2O_5 generated by animal types across all selected farms. Total P_2O_5 produced was 12,000 pounds/farm.

Types of storage systems available for producers is an important consideration in efficiently retaining nutrients and allowing enough storage to field apply the manure in an environmentally safe manner. Types of manure collection systems of the 58 farms can be best catagorized as; liquid systems (28); lots/barns/pasture (26) and daily haul (4).

For purposes of this report, the following definitions were used: *Daily Scrape and Haul*-No storage available, manure is hauled generally on a daily basis. Common in dairy operations with stanchion or tie-stall barn designs; *Paved and Unpaved Pads*-Areas where solid manure is stacked on either the ground or cement pads to allow storage through the winter months until fields are accessible for spreading; *Paved and Unpaved Lots*-Cement or gravel covered areas that confine cattle. Manure (solid) is often hauled once or twice a year although some are cleaned monthly: *Animal Barns*- Buildings used to house livestock. The floors can either be cement, such as in a normal frame barn, or commonly a dirt floor often found in pole barns. Manure (solid) is often hauled in spring and fall, although the barns housing young calves are usually hauled more frequently; *Earthen Pits*- A majority of these pits are designed to meet Minnesota Pollution Control Agency and Natural Resource Conservation Service standards. Bottoms are frequently lined with compacted clay or other near-impervious material. Pits are usually emptied once or twice a year and are not covered; and *Slurry Store*-Above ground steel tanks which are generally emptied once or twice per year. Tanks are generally not covered.

Amounts of N and P collected, lost in storage, and amounts retained for land application are summarized by collection systems in Table A.1.-5. Based on the N retained after collection (Figure 11), the dominant collection systems on the Central Sands are; animal barns (47%), earthen pits (27%) and pits under barns (16%). It appears that producers have the equipment facilities to store roughly three-fourths of the manure (based on retained N) and should not be subjected to applying manure during poor weather conditions. Daily scrape and haul systems pose difficult environmental challenges and field-applied losses after are high if not properly incorporated. The importance of this type of system, based on nutrients generated, is rather small.

Table A.1.-5. Manure N and P_2O_5 collected and storage losses by all livestock on all farms in 1994

	Nitrogen Pounds X 1000			Phosphate Pounds X 1000		
Livestock Type	Collected	Lost	Retained	Collected	Lost	Retained
Daily Scrape/Haul	59.4	14.9	44.5	26.2	0	26.2
Unpaved Lot	54.2	27	27.2	39.9	11.94	28.0
Paved Lot	8	4	4.0	5.6	1.7	3.9
Animal Barn	427.3	128.1	299.2	276.5	0	276.5
Paved Pad	8.8	1.9	6.9	3.6	0	3.6
Pit Under Barn	76.7	16.9	59.8	38.9	0	38.9
Slurrystore	9.4	2.1	7.3	3.8	0	3.8
Earthen Pit	238.8	71.8	167.0	100.0	0	100.0
Above Ground Tank	14.5	3.2	11.3	7.6	0	7.6
Poultry Pit	2.3	1.9	0.4	0.9	0	0.9
Compost	0.4	0.0	0.4	0.3	0	0.3
SUBTOTAL	**899.8**	**271.8**	**628.0**	**503.3**	**13.6**	**489.7**

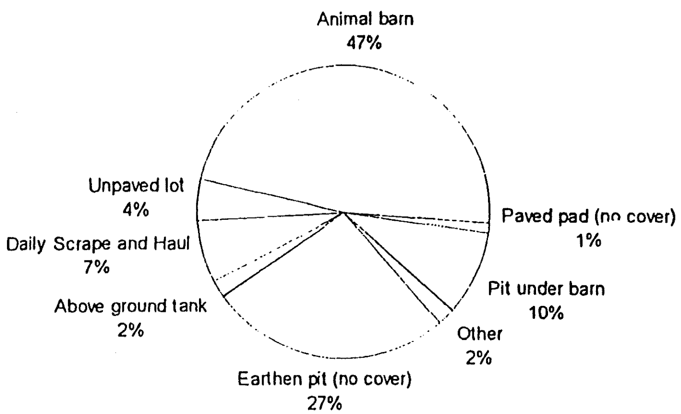

Figure A.1.-10. Contributions of total **nitrogen retained after storage** by manure collection systems.

Nutrient losses from collection and storage were estimated from accepted guidelines[9] for each individual storage system. Losses as a function of application methods and timing factors were calculated on a field-by-field basis (Table A.1.-6). Manure generated a total of 316,000 lb of "first year available" N. This represents 5,500 lb/N/farm.

The fate of manure-N has been summarized in a simple flow diagram (Figure A.1.-11). This diagram simplifies the complexities associated with N from excretion to "plant available". Over half of the "first year available" N (on a weight basis) was applied to corn (Figure A.1.-12). Alfalfa (15%) and small grains (14%) received the bulk of the difference.

Manure testing is a critical component in nutrient management planning. Approximately 10% of the producers had done some manure testing prior to this project. Usually these producers had tested the manure only once. Participants were offered manure and well water testing as part of the program. Due to the high variability found in manure analysis, individual tests greatly enhanced the value of the on-farm nutrient balance. Samples are currently being collected and analyzed.

[9] Livestock Waste Facilities Handbook, Midwest Plan Services, Iowa State University, Ames, Iowa. 1985.

Table A.1.-6. Distribution of applied manure to cropland, application and timing losses, and manure plant available nitrogen in 1993

	Manure Nitrogen Applied Pounds X 1,000			Nitrogen Losses Pounds X 1,000			
Crop	Total	NH4+ (Inorganic)	Organic N	Mineralized Organic N 1st Yr. Avail	Application Losses	Timing Losses	Manure-N First Yr. Available
	Pounds Manure Nitrogen X 1000						
Corn	311.9	166.1	145.8	46.5	29.7	13.7	169.2
Clover	15.5	8.6	7.0	2.3	1.5	0.9	8.5
Alfalfa	88.8	48.3	40.5	14.0	9.9	3.9	48.5
Small Grains	81.9	44.7	37.2	12.1	8.9	3.1	44.7
EdibleBeans	22.0	13.2	8.7	2.6	3.0	0.9	12.0
Pasture	18.7	11.2	7.6	2.9	4.1	0.8	9.2
Grasses	18.5	10.2	8.3	2.8	3.3	1.0	8.7
Sunflower	11.3	6.7	4.6	1.4	0.8	0.2	7.2
Other	12.4	6.9	5.6	2.0	0.5	0.5	7.8
TOTAL	**581**	**316**	**265**	**87**	**62**	**25**	**316**

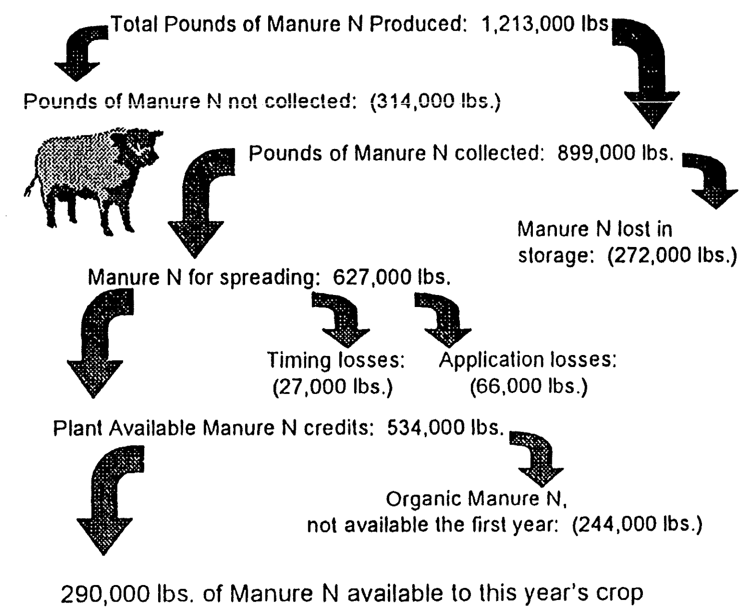

Figure A.1.-11. Fate of manure-N across all storage and management factors.

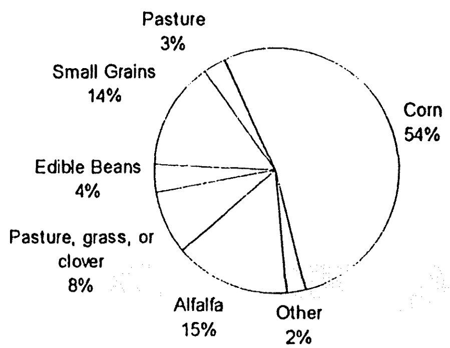

Figure A.1.-12. Distribution of "first year available" nitrogen by crop type calculated on a weight basis.

Relative Importance of N and P Sources on the Selected Farms: Farms on Non-Irrigated Outwash Soils

Commercial fertilizer (55%), manure (35%), and legume[10] (10%) contributed a total of 903,000 pounds of "first year available" N across all farms. Commercial fertilizer (23%) and manure (77%) contributed a total of 640,000 pounds of P_2O_5.

Commercial fertilizer (50%), manure (33%), and legume (17%) contributed a total of 525,000 pounds of "first year available N" to **corn acres** (Figure A.1.-13). This is an average N rate of 90 lb/A across all corn acres. The percent contributions from organic sources (accounting for a total of 50% of the inputs) is considerably higher than many other regions across state. These percentages are similar to southeast MN[11], however the total N inputs are considerably less on these outwash sands. The average N input in southeast MN was 167 lb/A. Proper crediting for these sources is critical in maintaining economic and environmental balances.

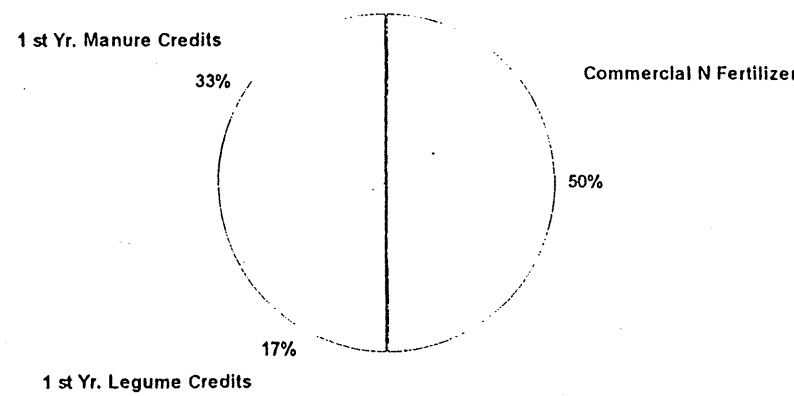

Figure A.1.-13. Relative contributions from fertilizers, manures and legumes on first year available N across all corn acres. Average N input across all corn acres 90 lb/A.

[10] Approximated value; total legume credits has been calculate however the value across all crops has not yet been determined.
[11] Effective Manure Management in Conservation Tillage Systems for Karst Areas, LCMR 1993-95.

Nitrogen Balances and Economic Considerations: Farms on Non-Irrigated Outwash Soils

The corn yield goal across all five counties was 70 bushels/A. Current University of Minnesota N recommendations to fulfill this goal is 60 lb/N/A (Figure A.1.-14). Factoring in all appropriate credits from fertilizer, legumes and manures, there was an over-application rate of 26 lb/N/A. Within this report, averages across fields (on a county basis) have been reported. More detailed analysis will follow which will "weight" the data to account for the wide range in field sizes.

These numbers are somewhat conservative in nature due to the fact that only "first year credits" from manure are included in the analysis. A vast majority of the producers did not have adequate records from the previous year (1993[12]) to accurately credits these sources. Also the producers generally did not have sufficient information regarding alfalfa stand densities prior to terminating the crop therefore an average credit of 100 lb/A was assumed. Statewide[13] recommended N credit for previous soybean crop is now 40 lb/A. However, UM recommendations also suggest reducing the credits to 20 lb/A on coarse-textured soils with low yield potential. We inadvertently used a 30 pound credit. Since the amount of acres in beans is minimal in this sample population, the error is probably insufficient. Based only on the N fertilizer replacement value, proper crediting could save these producers approximately $5/A[14] assuming no additional transportation and labor costs.

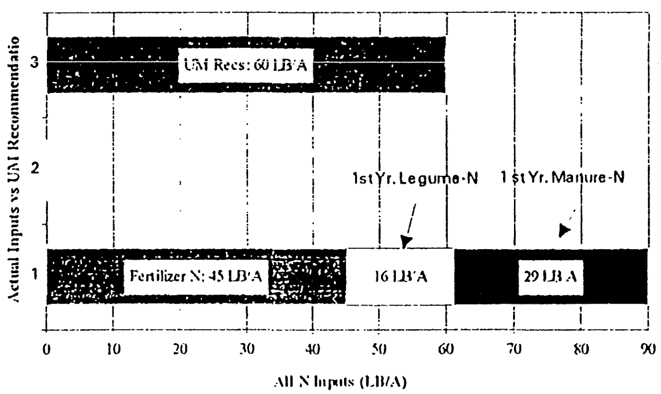

Figure A.1.-14. Crop N requirements based on University of MN recommendations in comparison to actual N inputs (fertilizer, legumes, and manure) across all corn acres. Total corn area in this analysis was 5,821 acres.

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12 Referring to any manure applications prior to those made in the fall of 1993.
13 G. Rehm, M. Schmitt, and R. Munter. Fertilizer Recommendations for Agronomic Crops in Minnesota. 1994. BU-6240-E.
14 Based on a nitrogen fertilizer price of $0.20/pound.

Balances were examined in more detail by lumping the **1994 corn acreage** into six different scenarios:

Scenario 1: N from fertilizer only; no manure or legume credits;
Scenario 2: Previously alfalfa (1993); no manure applied;
Scenario 3: Previously soybeans (1993); no manure applied;
Scenario 4: Previously a non-legume crop, manure applied;
Scenario 5: Previously a legume crop (1993), manure applied;
Scenario 6: Previously alfalfa (1992).

Nitrogen balances for all corn acres are broken down into these scenarios in Table 8. Fertilizer N rates specific to each scenario is illustrated in Figure 15. The commercial N rates in scenario 1 (no legumes, no manure) averaged 58 lb/A. One method to determine the credits attributed to the various organic contributions is to compare the subsequent commercial rates. **The following comments are based completely on the net differences in fertilizer N inputs comparing corn fields receiving only fertilizer N to the other scenarios:**

* Scenario #2: Producers reduced N fertilizer by 17 lb/A for the "first year" alfalfa credits (N rate averaged 41 lb/A);

* Scenario #3: Soybean acres were limited and no comparison were possible;

* Scenario #4 and #5: Producers also reduced fertilizer inputs on manured fields. Fertilizer N rates in scenario 4 (non-legume, manure applied) and scenario 5 (legume, manure applied) were reduced by 24 lb/A and 17 lb/A, respectively. These translate into reduction of 41 and 29%, respectively, in comparison to acres receiving only commercial N.

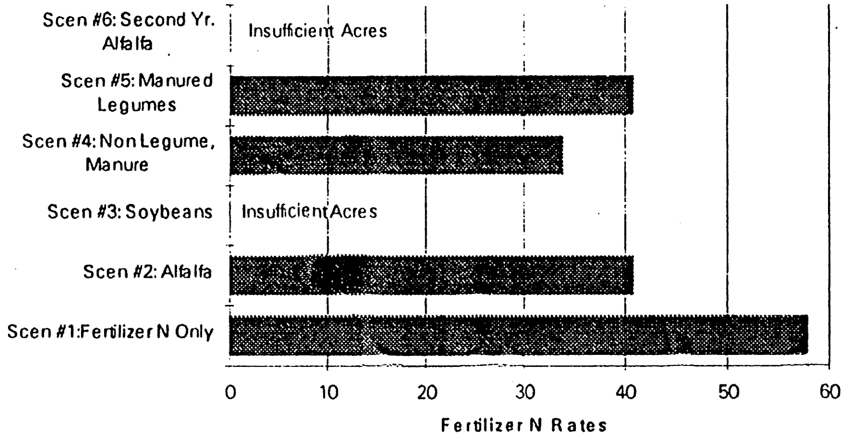

Figure A.1.-15. Commercial fertilizer N rates on corn by management scenario. See definitions for complete description of rotation and land application details.

Factoring in legume and manure credits into the process on a field-by-field basis, the amounts in excess of 1994 University of MN recommendations are illustrated in Figure A.1.-18. One of the huge advantages of the technique developed through the nutrient assessment process is the ability to examine in great detail the nutrient balances and make some inferences on where the biggest gains in water quality can be obtained through focused educational programs. Nitrogen balances are given in Table A.1.-8.

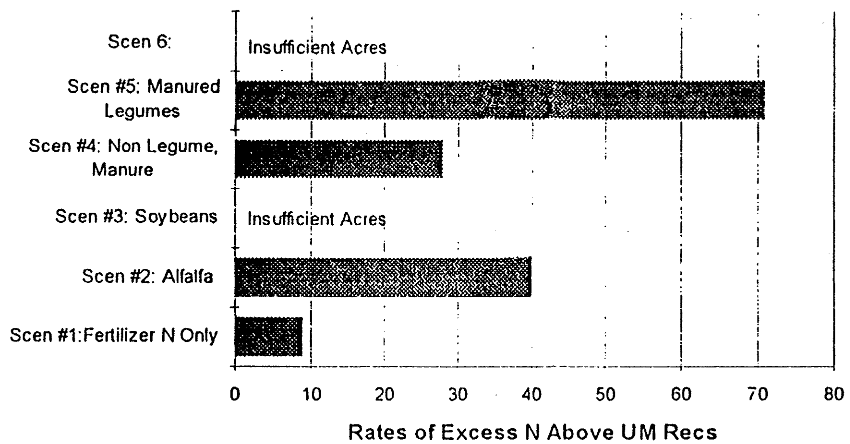

Figure A.1.-18. Amounts of N in excess of 1994 University of Minnesota recommendations across the different management scenarios. Analysis includes all 5,821 acres of corn.

Producers were making minor over-applications in scenario 1. Over-application rates in scenarios 2 and 4 ranged from 28-40 lb/A, respectively. Clearly the scenario where producers most severely over-applied N was on previous legume crops which received manure applications (scenario 5) prior to corn production.

Acreage distributions and N balances were then divided into two additional categories; ABOVE and BELOW UM recommendations. Data are given in Tables A.1.-8B and A.1.-8C respectively. Fifty-four (54%) of the total corn acres were classified into the ABOVE category. Excess amounts of N averaged 42 lb/Acre. The remaining acres (46%) were classified as BELOW UM recommendations. Shortage amounts of N average 23 lb/A and it is interesting to note that most of this shortage fell into scenario 1 (commercial N only).

Viewing the distribution of excess N from a water quality perspective, a helpful indicator is the cumulative excess N values found in Table A.1.-8A. These figures factor in both the total acres of any given scenario as well as the rate of excess (shortage) of N. Clearly where producers could gain the most N credits and make the biggest impact on water quality is to take the credits associated with scenario #4 (42% of the total) and #5 (35%). Figure A.1.-17 captures this concept by illustrating the relative excess N by the various management scenarios.

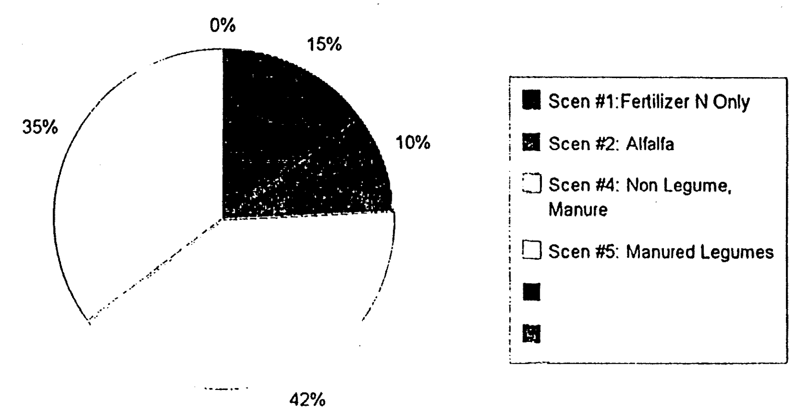

Figure A.1.-17. Relative contributions of total excess N by the different management scenarios across all corn acres.

Table A.1.-8A.
Nitrogen Inputs and Balances Across All Central Sands Non-Irrigated Areas

Scenario Number	Total Acres	PCN[1] (LBS/A)	PNC Total	Manure N (LBS/A)	Manure Total	Fert N (LBS/A)	Fert N Total	N Rec.[2] (LBS/A)	N Rec. Total	Excess (LBS/A)	Excess Total
1	2,399	0	0	0	0	58	138,801	69	165,793	9	21,891
2	360	100	36,000	0	0	41	14,627	1	330	40	14,297
3	24	30	720	0	0	40	960	60	1,440	0	0
4	2,165	0	0	59	128,227	34	73,231	72	156,192	28	60,662
5	733	64	46,931	58	42,231	41	29,858	27	19,822	71	52,306
6	140	52	7,240	0	0	42	5,915	29	4,006	21	2,980
TOTALS FOR ALL SCENARIOS	5,821	16	90,891	29	170,458	45	263,392	60	347,583	26	152,136

Table A.1.-8B.
Nitrogen Inputs and Balances-Excess Nitrogen-Across All Central Sands Non-Irrigated Areas

Scenario Number	Total Acres	PCN[1] (LBS/A)	PNC Total	Manure N (LBS/A)	Manure Total	Fert N (LBS/A)	Fert Total	N Rec.[2] (LBS/A)	N Rec. Total	Excess (LBS/A)	Excess Total
1	917	0	0	0	0	93	85,626	71	65,488	22	20,322
2	180	100	18,000	0	0	57	10,249	1	166	56	10,140
3											
4	1,218	0	0	70	85,356	40	49,297	69	83,892	42	51,139
5	715	60	42,723	51	36,368	49	35,373	38	26,932	63	44,876
6	59	54	3,190	0	0	64	3,756	16	950	47	2,797
TOTALS FOR ALL SCENARIOS	3,089	21	63,913	39	121,724	60	184,301	57	177,428	42	129,273

Table A.1.-8C.
Nitrogen Inputs and Balances Across Shortage Nitrogen,Acres - All Central Sands Non-Irrigated Areas

Scenario Number	Total Acres	PCN[1] (LBS/A)	PCN Total	Manure N (LBS/A)	Manure Total	Fert N (LBS/A)	Fert Total	N Rec.[2] (LBS/A)	N Rec. Total	Shortage (LBS/A)	Shortage Total
1	1,482	0	0	0	0	39	58,533	68	100,573	28	41,166
2											
3	24	30	720	0	0	40	960	60	1,440	0	0
4	947	0	0	41	38,357	22	21,108	80	75,796	17	15,901
5	18	30	540	21	378	30	540	60	1,080	9	158
6	42	50	2,100	0	0	14	606	40	1,680	25	1,070
TOTALS FOR ALL SCENARIOS	2,513	1	3,360	15	38,915	33	81,747	72	180,569	23	58,296

Scenario Definitions:

Scenario 1 = Acres receiving only fertilizer N; no PCN or manure applied.
Scenario 2 = Acres previously in alfalfa; no manure applied.
Scenario 3 = Acres previously in soybeans; no manure applied.
Scenario 4 = Acres receiving manure with no previous PCN.
Scenario 5 = Acres receiving manure with PCN.
Scenario 6 = Acres previously in alfalfa in 1991.

[1] PNC = Previous Crop Nitrogen credit.
[2] Recommendations based on yield goal, previous crop and the organic matter according to the University of Minnesota recommendations where soil nutrient test results were not available.

Conclusions and Summary of the Current Nutrient Management Practices on Non-Irrigated Central Sands

Fifty-eight farms, covering over 31,000 acres, participated in the FArm Nutrient Management Assessment Program (FANMAP) with staff from the Minnesota Department of Agriculture. Producers volunteered 2-4 hours of their time to share information about their farming operation. Producers were carefully selected to represent a wide diversity of management skills and farm characteristics. The overall purpose of the program was to develop a clear understanding of current farm practices regarding agricultural nutrients and utilize this knowledge for future water quality educational programs.

Nitrogen management on the Central Sands is challenging due to the nature of the soils and additional management skills required to manage organic N inputs. Manure accounts for approximately 33% of the 'first year available' N; legumes account for another 17%. Obviously proper crediting of both of these sources is needed to successfully manage N on these outwash sands. Yield goals varied tremendously on these outwash soils due to the wide range of organic matter content and available moisture holding capacity. The overall corn yield goals were 70 bu/A. Consequently, the nutrient inputs in general were significantly lower than most other regions of the state.

On corn acres where no previous manure or legume credits existed to confound the rate selection process, producers appear to be in excellent agreement with recommendations that were made by UM/MES. Corn acres which were above or below the UM recommendations were equally distributed.

Overall, producers reduced N fertilizer inputs following "first year" alfalfa by 17 lb/A. However, additional reductions (20-30 lb/A) could be made with a low probability of yield loss. One of the difficulties in the data collection process was obtaining reliable alfalfa information prior to stand termination. It appears that producers need the assessment tools for determining alfalfa stand densities and record keeping systems to aid in more effectively capturing alfalfa credits.

Producers were basically reducing commercial N inputs by 24 lb/A in scenarios where previous manure applications were made to non-legume crops such as corn. Producers were under-estimating the value of the manure by approximately 25 lb/A. It is a common practice to apply manure to old alfalfa stands which are followed by corn in the rotation. In this scenario, producers were found to reduce their commercial inputs by approximately 17 lb/A. However the combination of alfalfa and manure credits, coupled with the fertilizer (average of 40 lb/A), resulted in over-applications of 70 lb/A. In these situations, only a starter N application should be applied and would trim 20 to 30 lb/N/A from the N budget. Due to the low yield potentials of these soils, all the N requirements for corn will be supplied from alfalfa stands of 2 plants/ft or denser. Producers could capture a higher percentage of the "fertilizer replacement value" by applying the manure into other corn rotations. Approximately 50% of the corn acres did not receive any manure application so there is ample locations to apply the manure. From a water quality perspective, the most significant impacts could be made by improving the N crediting process in this particular cropping scenario.

Proper timing of N applications is one of the key management strategies that producers in this region can implement to minimize N leaching losses. Producers have been encouraged to avoid fall application on any coarse-textured soils. FANMAP determined that fall application of N was extremely rare; spring preplant and starter N accounted for 56% of applied N fertilizer with the remaining balance sidedressed. Timing and source selection of N fertilizers appeared to be in excellent agreement with current BMPs developed by MES in conjunction with MDA. A very high percentage of the N fertilizers were ammonium based products.

This area has a high diversity of storage/collection systems, most of which provide some opportunity for storage. The process of manure crediting is greatly simplified with manure storage systems that allow for a minimal number of land application events. Over 80% of the N retained after storage originated from a variety of systems that allowed for some storage benefits. In previously studies by the MN Extension Service, the nutrient value from manure has been found to be highly variable. Manure testing needs continual promotion as a fundamental part of a nutrient management plan. Only 10% of the producers had tested their manure previously to this project.

There were some very positive findings from this study. There is strong evidence that producers are voluntarily adopting the educational materials and strategies developed by the University of Minnesota/MN Extension Service. It is also evident that promotional activities need to continue and be specifically targeted to deliver the most recent technology and recommendations. Strong similarities exist in all existing FANMAP projects: producers are generally managing commercial N inputs successfully (although frequently using outdated recommendations) but continually under-estimate the N credits associated with manure and alfalfa inputs.

General Information: Farms Irrigated Potatoes

The Minnesota Area II Potato Growers Research and Promotion Council was contacted and a meeting took place with the chairman in February, 1995. The purpose of the meeting was to inform the Council of the specifics of the project and overall goals; obtain pertinent Area II information (i.e. locations of outwash sands and boundaries of Area II); and select potential candidates (potato growers) for the interviews. The Area II Council also served as an important link between the potato growers and the researchers; the Council made personal phone calls or visits to potential participants after the introduction letter (Appendix A-2) was mailed. Part of the criteria for consideration was that the farms needed to have sandy soils, be in Area II, and the potato acres needed to be irrigated. Potato growers in the Anoka sands plain were not selected do to their intense involvement with another project. Likewise, producers in the Red River Valley and Hollendale areas were eliminated for not being in Area II and no irrigation respectively. A list of all potential candidates was derived and it was decided, due to the small number of growers, to include all 37 potato growers who fulfilled the criteria in the project. Introduction letters (Appendix A-2), signed by the Commissioner of Agriculture, were mailed out to the 37 potato growers in March, 1995. The letter's intent was to identify: the overall LCMR project; the purpose of the nutrient assessment; why they were selected; and what types of information and amount of their time would be necessary to successfully complete the project. Letters were sent to 37 potato growers and 24 (65%) growers went through the interview process. Potato growers interviewed were from Otter Tail, Hubbard, Wadena, Stevens, Todd, Stearns, Morrison, Benton, Sherburne, and Isanti counties and the interviews were performed in March and April.

Nutrient Management Data Collection: Irrigated Potatoes

Inventory forms and data base design were patterned after a previous successful project[15]. A copy of the inventory form is included in Appendix A-2. Timing, rates and method of applications were collected for all nitrogen (N) and phosphate (P_2O_5) inputs (fertilizers, manures, and legumes) on **a field-by-field basis for all potato acres owned or rented**. There were 209 management areas (only potatoes) in the entire study with a management area being defined as a field or group of fields (managed by the same producer) that had the same nutrient inputs. If an individual field was not managed uniformly, it would be broken down into separate management areas. Soil and manure testing results were also collected if available (growers did not have any livestock or manure with the exception of one grower). Nutrient inputs and yields were specific for the 1994 cropping season. Crop types and manure applications (starting in the fall of 1993) were also collected from the 1993 season for purposes of 1994 nitrogen crediting. Long term yield data generally reflected the past 3 to 5 years.

[15]Effective Nitrogen and Water Management for Water Quality Sensitive Regions of Minnesota, LCMR 1991-93

Farm Size and Crop Characteristics of the Selected Farms: Irrigated Potatoes

Twenty four potato growers were interviewed during March and April, 1995. Total area covered by the interviews was 19,354 acres in 209 separate management areas. According to the 1994 Edition of Minnesota Agriculture Statistics total potato acres (predominately irrigated) excluding the Red River Valley and Hollendale areas total 24,900 acres in 1993 and 28,500 acres in 1994. The interview process inventoried approximately 68% of total acres (excluding the Red River Valley and Hollendale areas).Only one grower used any manure on his fields.

The potato acreage was divided into three categories according to when the potatoes matured (based on harvest dates). Early maturity is when the potato field is harvested before August 8; these potatoes generally are harvested for the fresh market and are concentrated in a cluster from Big Lake to St. Cloud. Medium maturity is when the potato field is harvested August 8 through August 31; generally these potatoes are also harvested for the fresh market although some are for processing and are also grown in a cluster from Big Lake to St. Cloud and in the Long Prairie and Little Falls area. Late maturity is when the field is harvested after August 31; Late potatoes are generally for processing and are grow in the Park Rapids area and in small areas by Becker and Morris. Potato growers operating in the fresh market often grow a variety of potatoes including Goldrush, Atlantic, Snowden, and Red Norlands. Also, fresh market growers tend to harvest potatoes August through September, in all three maturity groups. Potato growers operating in the processing markets generally harvest late and Russet Burbank is the variety grown on most acres. Yields varied according to the maturity of the potato from 291 cwt/A for early maturity potatoes to 421 cwt/A for late maturity potatoes using a five year average (Table A.1.-9).

Table A.1.-9
Average Yields by Maturity

Potato Harvest Timing	Fields	Acres	1993 Yield Cwt/A	1994 Yield Cwt/A	Average Yield[16] Cwt/A	Average Harvest Date
Early Maturity	12	883	292	288	291	July 27
Medium Maturity	64	4,570	353	359	373	Aug. 25
Late Maturity	133	13,901	410	420	421	Sept. 20
Totals/Average	**209**	**19,354**	**391**	**399**	**403**	**Sept. 10**

Current Management Techniques and Nitrogen Balances: Irrigated Potatoes

Commercial fertilizer containing nitrogen was used on all potato acres. Potato acres received an average of 243 lb/A of nitrogen as commercial nitrogen and 4.1 lb/A of nitrogen from previous crops (predominantly edible beans). Best Management Practices (BMPs)[16] developed for potatoes recommend applying 199 lb/A for a yield goal (five year average) of 410 cwt/A (Table A.1.-10) leading to a 48 lb/A over application on all potato acres averaged. N can also be credited from irrigation water if nitrate levels are over 10 ppm. 12 growers did test wells for nitrates but none had nitrate levels above 10 ppm, possibly do to the depth of the irrigation wells(most over 120 feet deep). Correct irrigation management can also help to reduce leaching of nitrate. Potato growers used several methods to determine soil moisture content for irrigation scheduling. The "feel" method or hand method was the dominate method used followed by experience(personal information on when to irrigate). Soil probing and plant appearance were among other methods used. The amount to apply was often determined by ET measurements and experience although growers often used several factors such as soil type, past rain fall, and forecasts to determine the amount to apply.

Table A.1.-10
Previous Crop and Nitrogen Applications

Potato Maturity	Acres	Yield Goal Cwt/A	Prev. Crop N Lbs/A	Fert. Apps. No.	Fert. N Lbs/A	Required N Lbs/A	Excess N Lbs/A
Early Maturity	883	295	6.7	3.3	214	137	82.8
Medium Maturity	4,570	383	6.3	3.6	225	184	49.1
Late Maturity	13,901	426	3.2	5.7	251	208	44.4
Totals	**19354**	**410**	**4.1**	**5.1**	**243**	**199**	**48.1**

Timing of N fertilizer applications is an important consideration in maximizing fertilizer use efficiency and minimizing environmental effects. Due to the high probability of leaching in these irrigated sandy soils, the overall strategy is to apply the N to closely match crop uptake. Best Management Practices (BMPs)[17] developed for irrigated potatoes focus on a number of timing issues. First, fall applied N is not recommended under any circumstances on sandy soils. In this study, there was no fall fertilization on early or medium maturity potatoes less than only 0.4% of the N fertilizers used on late maturity potatoes was fall applied (Figures A.1.-18, A.1.-19, and A.1.-20).

[16]Carl Rosen 1995. Best Management Practices for Nitrogen Use: Irrigated Potatoes (Draft).
[17]Carl Rosen 1995. Best Management Practices for Nitrogen Use: Irrigated Potatoes (Draft).

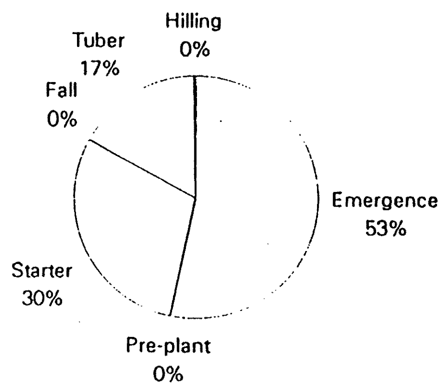

Figure A.1.-18. Percentage of total Commercial N applied for the 1994 potato season on early maturity potatoes.

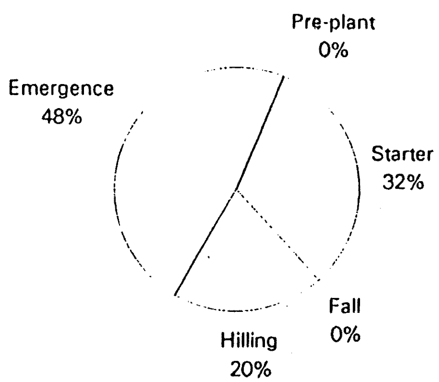

Figure A.1.-19. Percentage of total Commercial N applied for the 1994 potato season on medium maturity potatoes.

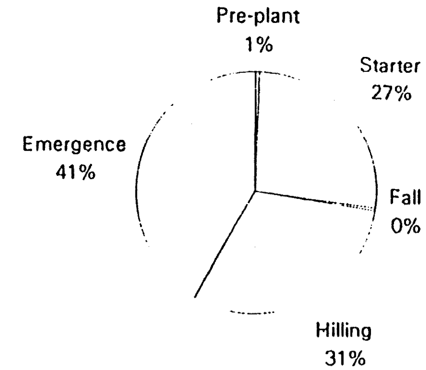

Figure A.1.-20. Percentage of total Commercial N applied for the 1994 potato season on late maturity potatoes.

Secondly, BMPs recommend a maximum of 40 lb/A in the starter (no N is recommended in a preplant application) to prevent early season leaching. Starter rates for early, medium and late maturity potatoes are 64, 72 and 67 lb/A respectively. It appears potato growers are over applying N in starter fertilizer by 20 to 30 lbs/A overall.

Another important BMP is to split additional applications of one half to one third of recommended N at emergence and one third of recommended N at last hilling for all potatoes with additional possible applications determined by petiole analysis. Fertigation is a recommended practice if based on petiole analysis and N is limited to 10 to 40 lbs/A n per application through the irrigation system. 13 of 24 growers were using petiole analysis (10 field test, 3 laboratory) to make management decisions. N applied through the irrigation systems was 0.4% of the total N for early maturity potatoes. 12% for the medium maturity, and 16.9% for the late maturity potatoes. Amounts of N applied though fertigation ranged from 7 to 28 lbs/A per application and appear consistent with the recommended BMP[18] amounts of 10 to 30 lbs/A per application. Also the source of the N used for potatoes is a key factor in preventing leaching. Fertilizers containing nitrate in the starter are not recommended and growers are generally following this recommended practice. Table A.1.-11 lists each source of N for each maturity group.

[18]Carl Rosen 1995. Best Management Practices for Nitrogen Use: Irrigated Potatoes (Draft).

Table A.1.-11 Nitrogen Sources Applied to Potatoes Pounds N X 1000							
Potato Maturity	Anh.NH_3	Urea	U.A.N	NH_4NO_3	Dry[19] Mix	$(NH_4)_2SO_4$	Total
Early Maturity	56.9	14.5	0.9	19.0	110.7	0	202
Total Percentage	28.2%	7.2%	0.4%	9.4%	54.8%	0%	100%
Medium Maturity	0	314.4	115.0	92.2	446.3	33.6	1001
Total Percentage	0%	31.4%	11.5%	9.2%	44.6%	3.4%	100%
Late Maturity	13.1	355.1	711.2	26.9	2391	0	3,497
Total Percentage	0.4%	10.2%	20.3%	0.8%	68.4%	0%	100%
Totals	**70**	**684**	**827.1**	**138.1**	**2948**	**33.6**	**4008**

Cover crops were established on potato fields after harvest on 6,342 acres of the total 19,354 acres covered in the survey with rye as the predominant choice for a cover crop (5,090 acres). Cover crops provide both soil erosion protection on sandy soils and also will take up residual N resulting in less leaching. N will then be released from the vegetation the following season. Early maturity and medium maturity potatoes were normally followed with a cover crop while late maturity potatoes generally did not have a cover crop.

Soil testing is a valuable tool for determining fertilizer requirements[20] of potatoes on sandy soils and was used on 13,213 (68%) out of 19,354 acres surveyed. Nitrate tests were also performed on 1037 (5%) of the total acres although the test is not a recommended practice for potatoes on sandy soils (nitrate has a tendency to leach). Results of the nitrate test (NO_3-N) shows a residual N of 8 to 48 lbs/A available for crop use. Average soil test results for each maturity group are shown in Table A.1.-12.

[19] Dry mix represents and array of formulations , which are dominantly ammonium based.
[20]George Rehm 1987. Unit 1 Soil Testing. AG-FO-3329.

Table A.1.-12 Soil Test Results						
Potato Maturity	Fields No.	Total Acres	Organic Matter %	pH	Bray Phosphorus PPM	Potassium PPM
Early Maturity	8	503	1.7	5.4	72	142
Medium Maturity	50	3,482	1.6	5.6	126	144
Late Maturity	86	9,228	2.1	5.9	66	134
Totals	**144**	**13,213**	**1.9**	**5.8**	**82**	**137**

Phosphorus required for potatoes, derived from soil tests and yield goals according to University of Minnesota recommendations[21], appear to be significantly less than actual amounts applied. The U/M recommendations for potatoes with soil test P levels (Bray-P-1) above 51 ppm and a yield goal of 400 to 499 cwt/A to receive 50 lbs/A of phosphorous. In contrast, the average amount of phosphorus applied in the survey was 148 lbs/A. Field testing (68% of all fields) showed a level of 82 ppm of phosphorus and a yield goal average of 410 cwt/A over all fields. Table A.1.-13 shows over application on all maturity groups in the survey with an average over application of 92 lbs/A.

Table A.1.-13 Phosphorus Recommendations						
Potato Maturity	Acres	Bray P[22]	Yield Goal	P Lbs/A Required[23]	P Lbs/A Applied	P Lbs/A Excess
Early Maturity	883	73	295	0	146	146
Medium Maturity	4,570	126	383	25	115	90
Late Maturity	13,901	66	426	50	159	109
Totals	**19,354**	**82**	**410**	**50**	**148**	**92**

[21]C. J. Rosen and R. C. Munter 1992. Nutrient Management for Commercial Fruit & Vegetable Crops in Minnesota. AG-BU-5886-F
[22]Bray P column is based on results from 68% of all fields
[23]Recommendations from University of Minnesota

Conclusions and Summary of the Current Nutrient Management Practices For Irrigated Potatoes on Sandy Soils

Twenty-four potato farmers covering over 19,000 acres, participated in the **FA**rm **N**utrient **M**anagement **A**ssessment **P**rogram (**FANMAP**) with staff from the Minnesota Department of Agriculture. Producers volunteered 2-4 hours of their time to share information about their farming operation. Producers were carefully selected to represent irrigated potatoes on sandy soils. The overall purpose of the program was to develop a clear understanding of current farm practices regarding agricultural nutrients and utilize this knowledge for future water quality educational programs.

Nitrogen management for potato growers on sandy soils is challenging due to the nature of the soils and additional management skills required to manage irrigation scheduling. The overall potato yield goals were 410 cwt/A and N inputs came primarily from commercial fertilizer. Only one grower had N contributed from manure and less than 5 lbs/A were contributed from previous legumes. Cover crops were used extensively for early and medium maturity potatoes; consistent with current BMPs.

Overall, producers were generally over applying N by 48 lbs/A according to recommendations from the U/M. In addition it appears potato growers could reduce their N rates in starter fertilizers by 35% from 67 lbs/A to the recommended 40 lbs/A according to U/M recommendations. Research on early maturing potatoes, especially the new varieties, will provide further assistance to potato growers. Proper timing of N applications is one of the key management strategies that producers in this region can implement to minimize N leaching losses. Producers have been encouraged to avoid fall application and research suggests this practice is being endorsed. Timing and source selection of N fertilizers appeared to be in excellent agreement with current BMPs developed by MES in conjunction with MDA. A very high percentage of the growers were using multiple split applications and N applications through fertigation were consistent with recommended practices also.

Soil testing was done on 68% of the potato acres providing information to assist the growers in correct fertilizer application amounts. In regard to Phosphorus, growers seem to be over applying by approximately 92 lbs/A according to U/M recommendations. Here again, research on additional varieties and early maturing potatoes will provide assistance to the potato growers.

There were some very positive findings from this study. There is strong evidence that producers are voluntarily adopting the educational materials and strategies developed by the University of Minnesota/MN Extension Service. It is also evident that promotional activities need to continue and be specifically targeted to deliver the most recent technology and recommendations.

Appendix

A-1

December 5, 1994 (612)297-3219

«MsMr» «FName» «LName»
«Address»
«City» «State» «Zip»

Dear «MsMr» «LName»:

I do not have to travel very far anywhere in the state of Minnesota to hear conversation about agriculture and what effects our farming profession could potentially have on our groundwater resources. These conversations are universal --- from the local coffee shop to Extension events; the concerns have been carried over to the Capitol as well. Environmental responsibilities have been on the increase over the past few years and trends strongly indicate a growing public concern. You, as a farmer in the central sands plain, may already feel the added responsibilities.

Our farming industries on the central sands plain are highly visible and are specialized segments of Minnesota agriculture that will have to be ready to respond to the new environmental challenges ahead of us. Regulations can be avoided down the road if we can provide adequate educational support and research based technology to our farming community.

Last summer, the University of Minnesota, the Minnesota Extensions Service and the Minnesota Department of Agriculture (MDA) received a research/educational grant from the Legislative Commission on Minnesota Resources. You may already be aware of some activities going on at the West Central Experiment Station and at the Central Minnesota Economic Development Research & Education Center (previously known as the Staples Irrigation Center) as a result of this grant.

One project is studying the influence of potassium on ridge-till crops compared to conventional methods of planting. Another project is the study of manure applied to corn at various times and with various methods such as sidedress compared to broadcasting and incorporation.

Another critical component of this project involves **you!** We simple do not have adequate information on how our pork producers and dairy farmers handle their nitrogen sources .... whether it is from fertilizers, manures, or legumes. It is critical that there is a logical "link" between what the research community is doing and what is currently being practiced in the real world of production agriculture.

I am asking you, along with 49 other farmers to participate in a survey of nitrogen and phosphorus management practices. I have summarized a series of questions that you may already be asking yourself:

WHY WAS I SELECTED?

This project focuses on **farms on the Central Sands Plain** from Hubbard, Becker, Ottertail, Wadena and Todd counties. Your name was suggested as a possible participant by your local County Extension Educator.

WHO ELSE WAS SELECTED?

Due to the high cost associated with this type of data collection, we will be limited to fifty (50) participants. It is critical that the farmers selected are representative of farming practices typical for the central region of Minnesota.

WHAT KINDS OF QUESTIONS WOULD I BE ASKED?

You will be asked questions about each individual field that you farm. Questions include such things as crop type, nitrogen fertilizer rates, timing of applications, manure applications, cost information, soil test results, and factors motivating nitrogen decisions. Questions will be limited to the 1993 and 1994 cropping season.

HOW LONG WILL THE MEETING LAST?

The meeting time will depend on the number of individual fields you farm and how complex your own inventory will be. Most interviews would last between 1 to 2 hours.

HOW WILL THIS INFORMATION BE TREATED? WILL IT BE PUBLICIZED?

No individual results will be reported in this study. The MDA will keep your information confidential. Only composite results will be published.

WHEN WILL THE MEETING TAKE PLACE AND WHERE?

We would like to visit with you, at your convenience, at your farm. Interviews would occur sometime in mid-to-late December.

WHO WILL COME TO MY FARM?

Denton Bruening, a research assistant for the MDA, will be visiting with you and conducting the interviews. Denton is from a small farm in Lincoln county and is well

acquainted with farm operations. He has conducted over 150 similar interviews with farms in central, south central, and southeastern Minnesota.

WHAT CAN I GAIN BY PARTICIPATING IN THIS PROCESS?

You will be making a significant contribution to our agriculture community. This information will provide a "benchmark" on where we are at in terms of nitrogen and manure management strategies. "Benchmark" information can then be used to determine the effectiveness of future educational programs.

Manure analysis, as well as domestic well analysis for nitrates, will be offered free to each cooperator. At the completion of the study, we will also provide each participant with a summary of the results and conclusions.

I AM INTERESTED .... WHAT WILL HAPPEN NEXT?

You will be contacted by Mr. Thomas Hovde your county extension educator within the next two weeks. This will be your opportunity to ask any additional questions you may have. You will then be asked if you would like to participate in the interview. Interview times will be set up at a later date when Denton calls you for directions and to answer any additional questions you may have.

I hope you join the University of Minnesota, the Minnesota Extension Service, as well as the Minnesota Department of Agriculture in this project.

Sincerely,

Elton R. Redalen
Commissioner

ERR:DLB/clj

NITROGEN MANAGEMENT INTERVIEW CONTROL FORM-Dryland

June 21, 1995

Farm Number____________________

NAME______________________________________ PHONE_____________

ADDRESS____

____

DIRECTIONS____

____

DATE__________________________ TIME________________________

D:\data\intervie.doc

MAP CONTACT:

WATER TESTS:

LIQUID MANURE TESTS:

SOLID MANURE TESTS:

BROCHURES:

General Notes:

NITROGEN MANAGEMENT INTERVIEW FORM

Farm Number____________________

DATE___________________________ TIME________________________

I.BASIC FARM CHARACTERISTICS.

Years operated_______________

Acres_______ Owned_______ Rented in_______ Rented out___ Farm type:

Cash crop______________ Mixed_________

Type of Livestock________________

Main Crops______________ ______________

Herd average (lbs of milk):______________________________

Recent Acreage Changes(Last three years): Y or N_____

Acreage_______________________Year__________

Planned Acreage Changes(Next five years): Y or N_____

Acreage_______________________Year__________

Do you use a crop consultant?_____

Services:____

____

Name and Co.____

____

How many full time equivalents are provided by:

Family:____________ Hired Labor:___________

What is your soil type?_______________________________________

Note:____

III.LIVESTOCK AND DAIRY ANIMALS.(1 Of 3)

General description of operation:______________________________

____

____

Recent changes Animal(last three years):____________________________

____

Planned changes Animal(next five years):____________________________

____

Now, as a basis for determining total manure production, we need to calculate the average number of animals and their average weights during 1993 and 1994.

Dairy:

Breeds: Ave._%_of_herd

____________________ ____________

____________________ ____________

Ave # animals during yr. _1993_ _1994_ "AVG "

11 - cows, milking and not ______ ______ ______

12 - calves less than 1 yr. ______ ______ ______

13 - rep. heifers 1-2 yrs. old ______ ______ ______

15 - feeder steers ______ ______ ______

avg. weight(steers) ______ ______ ______

avg. weight at sale ______ ______ ______

Farm Number______________

IV.Livestock and dairy operations (2 of 3)

Swine:

Type of operation: (check each applicable catagory)

_____ farrow _____ farrow to finish _____ finishing

For 1994 estimate number of hogs to be sold

Ave # animals during year _1993_ _1994_ "AVG "

21 - Boars ______ ______ ______

22 - Sows ______ ______ ______

Farrow to feeder:

23 - Pigs sold (total) ______ ______ ______

Pigs on hand(ave) ______ ______ ______

Weight of pigs sold ______ ______ ______

Farrow to finish:(slaughters raised from birth)

25 - Slaughters sold(total)______ ______ ______

Slaughters on hand ______ ______ ______

Weight of slaughters sold ______ ______ ______

Finishing only:

24 - Slaughters sold(total)______ ______ ______

Slaughters on hand(ave)______ ______ ______

Weight of feeders purchased______ ______ ______

Weight of slaughters sold ______ ______ ______

Notes____

____

____

Farm Number________

Livestock and dairy operations (3 of 3)

Beef:Type of operation: ______ combined cow-calf/feedlot oper.

_______Cow-calf operation ______ feedlot (finishing) operation

Breeds: Ave._%_of_herd

__________________ ____________

__________________ ____________

We are trying to determine the number of beef that are raised on your farm. In the ON HAND category please list the average number of beef you had on hand for the year.

Ave # animals during yr. _1993_ _1994_ "AVG "

31 - Bulls ______ ______ ______

32 - Cows ______ ______ ______

Cow-calf operation:

33 - Calves sold (total) ______ ______ ______

Calves on hand ______ ______ ______

Avg. age at sale ______ ______ ______

Feedlot operation:

34 - Feeders sold (total) ______ ______ ______

Feeders on hand ______ ______ ______

Avg. weight at purch ______ ______ ______

Avg. weight at sale ______ ______ ______

Calf to finish:(birth to slaughter)

35 - Feeders sold (total) ______ ______ ______

Feeders on hand ______ ______ ______

Avg. weight at sale ______ ______ ______

IV.MANURE HANDLING; EXCLUDING APPLICATION

MANURE STORAGE:

1---No storage, daily scrape and haul ________

2---Unpaved lot__________

3---Paved lot_____________

4---Animal barn____________

20---HALF BARN HALF LOT

If you have a solid, Semi-solid ,or liquid storage what type?

5---Paved pad, covered_______________

6---Paved pad, uncovered_______________

7---Drained storage, covered____________

8---Drained storage, uncovered____________

9---Storage building_____________

10--Pit under barn _______________

11--Above ground tank, concrete______________

12--Above ground tank, steel (Slurrystore)_____________

13--Unpaved pad, covered_____________

14--Unpaved pad, uncovered_____________

15--Outside earthen storage pit, covered_______________

16--Earthen storage pit, uncovered_______________

17--lagoon_____________

18--Poultry pit___________________

19--Compost system___________

GENERAL DESCRIPTION:____________________________________

List the manure collections in terms of livestock type to each system. Account for each system identified on page 6.

System 1: **Codes**_________ **TiS**

20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (APPROX 0-50LB)
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS BOARS)
26--Mature Hogs(with young 0-20LB)

Conveyed_____

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months_______
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LI1QUID 2-SOLID)

Months_______
SPREADING FREQUENCY:

SPEADER CAP:________

UNITS:________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months
______	_____	________
______	_____	________
______	_____	________
______	_____	________
______	_____	________
______	_____	________

System 2: **Codes**_________ **TiS**

20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 0-50LB)
22--Feederpig days (APPROX 0-50LB)
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS, BOARS)
26--Mature Hogs(with young 0-20LB)

Conveyed_____

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months_______
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LI1QUID 2-SOLID)

Months_______
SPREADING FREQUENCY:

SPEADER CAP:________

UNITS:________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months
______	_____	________
______	_____	________
______	_____	________
______	_____	________
______	_____	________
______	_____	________

System 3: **Codes**_________ **TiS**

20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX 50LB)
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS,BOARS.REPLACE)
26--Mature Hogs(with young 0-20LB)

Conveyed_____

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months_______
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LI1QUID 2-SOLID)

Months_______
SPREADING FREQUENCY:

SPEADER CAP:________

UNITS:________
(GAL, BUSH, TON)

Animal Type	Number	Time In System or Months
______	_____	________
______	_____	________
______	_____	________
______	_____	________
______	_____	________
______	_____	________
______	_____	________

System 4: **Codes**_________ **TiS**

20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX 50LB)
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS,BOARS)
26--Mature Hogs(with young 0-20LB)

Conveyed_____

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months_______
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LI1QUID 2-SOLID)

Months_______
SPREADING FREQUENCY:

SPEADER CAP:________

UNITS:________

Animal Type	Number	Time in System or Months
______	_____	________
______	_____	________
______	_____	________
______	_____	________
______	_____	________

System 5: **Codes**__________

Conveyed_____
50LB)

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER
Hogs(SOWS,BOARS.REPLACE)

TiS 20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature
26--Mature Hogs(with young 0-20LB)

Months_______
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LI1QUID 2-SOLID)

Months_______
SPREADING FREQUENCY:

SPEADER CAP:________

UNITS:________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

System 6: **Codes**_________

Conveyed_____
50LB)

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

TiS 20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS,BOARS)
26--Mature Hogs(with young 0-20LB)

Months_______
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LI1QUID 2-SOLID)

Months_______
SPREADING FREQUENCY:

SPEADER CAP:________

UNITS:________

Animal Type	Number	Time in System or Months

System 7: **Codes**__________

Conveyed_____
50LB)

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER
Hogs(SOWS,BOARS.REPLACE)

TiS 20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature
26--Mature Hogs(with young 0-20LB)

Months_______
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LI1QUID 2-SOLID)

Months_______
SPREADING FREQUENCY:

SPEADER CAP:________

UNITS:________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

System 8: **Codes**_________

Conveyed_____
50LB)

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

TiS 20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS,BOARS)
26--Mature Hogs(with young 0-20LB)

Months_______
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LI1QUID 2-SOLID)

Months_______
SPREADING FREQUENCY:

SPEADER CAP:________

UNITS:________

Animal Type	Number	Time in System or Months

Farm Number____________________

IV.MANURE HANDLING; EXCLUDING APPLICATION

MANURE HANDLING SYSTEM GENERAL QUESTIONS

GIVEN DAILY SCRAPE AND HAUL

If you were to build a manure handling system, liquid or solid, what type would it be?______________________________

What do you think the total cost would be?____________________

Is cost sharing available in your area?______________________

If so, do you know how much you could get on the system you identified above?____________________________________

Compared to your daily scrape and haul system, how do you think the system identified above would affect the amount of the following nutrients provided by your manure? Think now about the amounts made available to crops. (Example answers: no change, 50%, more, etc.)

N __________

P __________

K __________

Why haven't you installed it?__________________________

____

Will you, or under what conditions would you reconsider?

____

____

Notes____

____

Farm Number__________________

IV.MANURE HANDLING

MANURE HANDLING SYSTEM GENERAL QUESTIONS

GIVEN LONG TERM STORAGE

When did you install last system______________________________

Previous system____

Approximate installation cost (whole system) ________________ Labor savings or loss compared to previous system ____________

____

Other savings or extra costs from previous system ____________

____

Motivating Factor_______________________________________

____

Second thoughts____

Notes____

____

V. OFF FARM MANURE PURCHASE; GENERAL QUESTIONS

System number_______ (101 or more)

If you purchase, or receive free, manure:

Animal Type	Number	Time in System or Months
______	______	______
______	______	______
______	______	______

OR

AMOUNT RECEIVED_________ BUSHELS, GALLONS TONS____________

IS THIS TOTAL AMOUNT OR PER ACRE?___________

What form is it? (1-liquid 2-solid)_______________

On what basis do you purchase it? (Volume, analysis, etc)

____

ANALYSIS INCLUDE ON ANALYSIS PAGE

On what basis do you pay for it?________________________________

Total cost________________ Cost per unit________________________

Does the cost above include: Unit description?___________

-transport to your farm?___________ application?___________

How do you determine and monitor app.____________________________

Total tons of manure purchased:________ (may be calculated by multiplying ton/acre by acres on page 19.)

Do you sell or give away any manure? How much?

Tons________ Gallons__________ Bushels__________

OR

Animal TYPE_______ NUMBER______ TiS Code_______

Farm Number____________________

VII. CROPS AND ROTATIONS

Please describe your general rotation pattern:

____

Do you part. in ASCS Comm. Prog.?_________ Does it affect your rotations?____.

How many acres were planted to the following crops

Year	__1993__	__1994__	__"AVG"__
Acres in:			
CRP/ RIM	________	________	________
CORN	________	________	________
Soybeans	________	________	________
Small grains	________	________	________
Alfalfa	________	________	________
Pasture	________	________	________
Edible beans: type____	________	________	________
Sunflowers	________	________	________
Sugar beets	________	________	________
Peas	________	________	________
Sweet corn	________	________	________
POTATOES	________	________	________
Buildings\roads	________	________	________
Other____________	________	________	________
Other____________	________	________	________
____________	________	________	________
Total (AS IN SEC.I)	________	________	________

Farm Number____________________

VIII. IDENTIFICATION OF MANAGEMENT AREAS.

We are attempting to analyze crop management differences across your farm. Before considering N applications and irrigation more specifically, we need to identify the areas you manage differently. We are primarily interested in areas which are irrigated AND/OR to which you apply commercial N, follow legumes in rotation (soybeans or alfalfa [2 years]), or apply manure. All combinations of these four practices, plus differences in crops define separate management areas. For example, irrigated cont. corn w/ scrape and haul manure differs from an identical area except that it receives liquid manure.(Differences in physical characteristics may also determine management areas. The map of the farm would be good here.){Identify the most productive field with √ in NOTES column.}

1-Conventional 2-Conservation 3-Notill 4-Ridgetill

AREA #	CROPS 94 - 93 - 92	ACRES	TILL? √	MAN?	*N*?	NOTES

Farm Number___________ CONTINUED

AREA #	CROPS 94 - 93 - 92	ACRES	TILL? √	MAN?	*N*	NOTES

Identify most productive field with a checkmark.

Farm Number________

Did you have analysis done on your manure? _____

System Number___ Date of last test?________

Percentage?___ Per gallon?___ Per ton?___

Avail N____ Total N____ P205____ K20____

System Number___ Date of last test?________

Percentage?___ Per gallon?___ Per ton?___

Avail N____ Total N____ P205____ K20____

System Number___ Date of last test?________

Percentage?___ Per gallon?___ Per ton?___

Avail N____ Total N____ P205____ K20____

System Number___ Date of last test?________

Percentage?___ Per gallon?___ Per ton?___

Avail N____ Total N____ P205____ K20____System Number___

Test lab where analysis is done______________________________

Cost of analysis____

If you have not had a recent test, Why?__________

1--Too Expensive 2--Not Accurate 3--No Time 4--other

Notes____

____

Farm Number___________

MANURE APPLICATIONS:(2 of 2)

List the destination of the manure from:(Systems, barns, and lots)

Include EACH application as a separate entry.

(Don't forget to include application of off farm manure produced off the farm, regardless of who applies it). **A**mount **P**er **A**cre column is for manure applied where amount applied per acre is known. Measure column

1--bushel per acre 2--gallon per acre 3--tons per acre

<--------------THIS------------------->OR<------THIS---------->

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________

NOTE: Be sure that you have accounted for 100% of the collected manure from each manure handling system. You also need to make sure that all manured areas are accounted for here!!! Don't forget off farm manure!!!!

List below any manure system collected but not available and

why:____

_______________ ______________________________________

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________

FARM NUMBER____________

DEFINITION PAGE FOR COMMERCIAL NITROGEN

Growth stages can be:

1-Fall

2-Spring preplant

3-Starter (with the planter)

4-Emergence (0-2 inches)

5-Early sidedress (2-8 inches)

6-Late sidedress (8 inches to harvest) 7-Other

Type of nitrogen applied *DEFINE STARTERS*

11-Anhydrous ammonia

12-urea

13-U.A.N. (solutions or liquid nitrogen)

14-Ammonium nitrate

15-Liquid starter 16-Dry mix(urea or unknown) 17-Other

Form of nitrogen:

21-gas (NH_3)

22-liquid

23-dry

24-other

Application method: Define method of planter app. from bellow!!

(SAME FOR MANURE)31-injected 32-broadcast

33-incorporated (include broadcast fields worked in 2 days)

34-banded (side dress) 35-irr 36-other

37-Knived in (man only) 38-Swept in (man only)

XI. COMMERCIAL FERTILIZER APPLICATIONS (N, P, and K).**careful**

MGMT AREA #__________ Crop Year__________

Application_#	1	2	3	4
App. date				
Growth stage				
Nit type (anhydrous,urea,etc)				
Fert. form (dry, liquid, gas)				
Analysis(% N,P,K)*ASK IF %*				
Lbs fert. (FOR %)				
OR Lbs. nut. **(ACTUAL)**				
App. method(broad,inj,etc)				
Nitrif. inhib.? (N-SERV)				
Fert. Cost (mat. or nut./lb.)				
Custom App Cost				
Appl. time (if self app, hrs)				

Last soil test in this area?____ ______________________________

By who?Crop consultant:______________________________

Lab:______________________________

Nitrogen results:

Organic matter %:____ or low/med/high____ or derived number:_____

Nitrate soil test: ppm:_____ pounds per acre:_______

pH:____ Olson test: ppm:_____ pounds per acre:_______

Bray 1 (low bray): ppm:_____ pounds per acre:_______

Potasium (K2o):____

Affect on applications?______________________________

Farm Number__________________

XI.COMMERCIAL FERTILIZER APPLICATIONS (N, P, and K)

Changes over the last three years______________________________

____

Why______________________________

XII.IRRIGATION

Do you irrigate any farm land?______

Mgmtarea	In./year	Type of irrigator	N-P-K Applied with Irr	Date

Note______________________________

FARM NUMBER____________________ XII. Yield info

CORN, POTATOES AND EDIBLE BEANS (by management area)

PEAS SOYBEANS YIELD

AREA	ROT.	MAN.?	1993	AVG	GOAL	1994

NOTES____

Did this survey fairly represent your farm and manure managment practices and the amounts applied?______ If not why not?______

____

Would you like the manure management plan?_______

FARM NUMBER____________________

THANK YOU FOR YOUR TIME AND EFFORT. AS I SUMMARIZE THE RESULTS, AN ADDITIONAL QUESTION, OR THE NEED FOR SOME CLARIFICATION MAY ARISE.IF SO, I HOPE I CAN GIVE YOU A CALL TO GET THE ADDITIONAL INFORMATION.

AS INDICATED BEFORE, WE WILL BE CONTACTING YOU LATER THIS YEAR FOR INFO REGARDING YOUR 1992 YIELDS AND IRRIGATION APPLICATIONS.

[WHAT ABOUT MANURE TESTING]!!!!!!!!

THANKS AGAIN!!!!!!!!!!!!!!!!!!!!!!!!!

CHECKLIST FOR COMPLETENESS AND CONSISTENCY. Take a minute to check these out before the farmer is freed.

1. Total acreage on the crop summary (p. 14) must agree with total land on p. 1 ._____

2. Acreages of mgmt areas (p. 15-16) must be reconciled with crop summary (p. 14)._____

3. All management areas (p.15-16) must be supported by appropriate supporting info re irrigation, manure apps and commercial N apps (p 20-22)._____

4. Manure applications (p. 19) must account for all collected manure (p. 6-10)._____

7. All cash crops acres must be accounted for on the yield sheet (p. 23)._____

Appendix

A-2

March 1, 1995

(612)297-3219

«MsMr» «FN» «LN»
«Address»
«City» «State» «Zip»

Dear «MsMr» «LN»:

I do not have to travel very far anywhere in the state of Minnesota to hear conversation about agriculture and what effects our farming profession could potentially have on our groundwater resources. These conversations are universal --- from the local coffee shop to Extension events; the concerns have been carried over to the Capitol as well. Environmental responsibilities have been on the increase over the past few years and trends strongly indicate a growing public concern. You, as a potato farmer may already feel the added responsibilities.

Our potato farming industry is a highly visible and specialized segment of Minnesota agriculture that will have to be ready to respond to the new environmental challenges ahead of us.

During the summer of 1993, the University of Minnesota, the Minnesota Extensions Service and the Minnesota Department of Agriculture (MDA) received a research/educational grant from the Legislative Commission on Minnesota Resources. You may already be aware of some activities going on at the Central Minnesota Economic Development Research & Education Center (previously known as the Staples Irrigation Center), and at the University of Minnesota as a result of this grant.

One project was the development of an "in-the-field" petiole sap test to test the nitrate level in potato's. Another project is to develop more accurate weather forecasts and have more availability of forecasts to farmers.

Another critical component of this project involves **you!** We simple do not have adequate information on how our potato farmers handle their nitrogen sources .... whether it is from fertilizers, manures, or legumes. It is critical that there is a logical "link" between what the research community is doing and what is currently being practiced in the real world of production agriculture.

I am asking you, along with other potato farmers to participate in a survey of nitrogen and phosphorus management practices. I have summarized a series of questions that you may already be asking yourself:

WHY WAS I SELECTED?

This project focuses on **potato farms** in the Area II potato region. Your name was randomly drawn from the Region II Area Potato Farmers.

WHO ELSE WAS SELECTED?

Due to the high cost associated with this type of data collection, we will be limited to thirty (30) participants. It is critical that the farmers selected are representative of farming practices typical for the Area II section of Minnesota.

WHAT KINDS OF QUESTIONS WOULD I BE ASKED?

You will be asked questions about each individual potato field that you farm. Questions include such things as crop type, nitrogen fertilizer rates, timing of applications, manure applications, cost information, soil test results, factors motivating nitrogen decisions and factors affecting irrigation decisions. Questions will be limited to the 1993 and 1994 cropping season.

HOW LONG WILL THE MEETING LAST?

The meeting time will depend on the number of individual fields you farm and how complex your own inventory will be. Most interviews would last between 1 to 2 hours.

HOW WILL THIS INFORMATION BE TREATED? WILL IT BE PUBLICIZED?

No individual results will be reported in this study. The MDA will keep your information confidential. Only composite results will be published.

WHEN WILL THE MEETING TAKE PLACE AND WHERE?

We would like to visit with you, at your convenience, at your farm. Interviews would occur sometime in early-to-mid March 1995.

WHO WILL COME TO MY FARM?

Denton Bruening, a research assistant for the MDA, will be visiting with you and conducting the interviews. Denton is from a small farm in Lincoln county and is well acquainted with farm operations. He has conducted over 150 similar interviews with farms in central, south central, and southeastern Minnesota.

WHAT CAN I GAIN BY PARTICIPATING IN THIS PROCESS?

You will be making a significant contribution to our agriculture community. This information will provide a "benchmark" on where we are at in terms of nitrogen and manure management strategies. "Benchmark" information can then be used to determine the effectiveness of future educational programs. Hopefully, regulations can be avoided down the road if we can provide adequate educational support and research based technology to our farming community from this benchmark information.

Manure analysis, as well as domestic well analysis for nitrates, will be offered free to each cooperator. At the completion of the study, we will also provide each participant with a summary of the results and conclusions.

I AM INTERESTED .... WHAT WILL HAPPEN NEXT?

You will be contacted by a Region II Area Potato representative within the next week. This will be your opportunity to ask any additional questions you may have. You will then be asked if you would like to participate in the interview. Interview times will be set up at a later date when Denton calls you for directions and to answer any additional questions you may have.

I hope you join the University of Minnesota, the Minnesota Extension Service, Area II Potato Research and Promotion Council, as well as the Minnesota Department of Agriculture in this project.

Sincerely,

Elton R. Redalen
Commissioner

ERR/DLB:clj

MANAGEMENT INTERVIEW CONTROL FORM

POTATO

March 6, 1995

Farm Number______________________________

NAME______________________________ PHONE__________

ADDRESS______________________________

____

DIRECTIONS______________________________

____

DATE______________________ TIME__________

D:\data\intervie.doc

WATER TESTS:

LIQUID MANURE TESTS:

SOLID MANURE TESTS:

BROCHURES:

General Notes:

MANAGEMENT INTERVIEW FORM

Farm Number________________

DATE______________________ TIME____________________

I. BASIC FARM CHARACTERISTICS.

Years operated____________

Acres_____ Owned______ Rented in______ Rented out___

Farm type:

POTATO:___________ Mixed_______

Type of Livestock____________

Main Crops____________ ____________

Recent Acreage Changes(POTATO): Y or N____

Acreage__________________Year________

Planned Acreage Changes(POTATO): Y or N____

Acreage__________________Year________

Do you use a crop consultant?____

Services:______________________________

____

Name and Co.______________________________

____

How many full time equivalents are provided by:

Family:__________ Hired Labor:_________

Note:______________________________

III. LIVESTOCK AND DAIRY ANIMALS. (1 Of 3)

General description of operation: ______________________________

____

____

Recent changes Animal (last three years): ______________________

____

Planned changes Animal (next three years): _____________________

____

Now, as a basis for determining total manure production, we need to calculate the average number of animals and their average weights during 1993 and 1994.

Dairy:

Breeds:	Ave._%_ of _ herd
______________	__________
______________	__________

Ave # animals during yr.	_1993_	_1994_	"AVG "
11 - cows, milking and not	_____	_____	_____
12 - calves less than 1 yr.	_____	_____	_____
13 - rep. heifers 1-2 yrs. old	_____	_____	_____
15 - feeder steers	_____	_____	_____
avg. weight (steers)	_____	_____	_____
avg. weight at sale	_____	_____	_____

Farm Number______________

IV. Livestock and dairy operations (2 of 3)

Swine:

Type of operation: (check each applicable category)

_____ farrow _____ farrow to finish _____ finishing

For 1994 estimate number of hogs to be sold

Ave # animals during year	_1993_	_1994_	"AVG "
21 - Boars	_____	_____	_____
22 - Sows	_____	_____	_____
Farrow to feeder:			
23 - Pigs sold (total)	_____	_____	_____
Pigs on hand (ave)	_____	_____	_____
Weight of pigs sold	_____	_____	_____
Farrow to finish: (slaughters raised from birth)			
25 - Slaughters sold (total)	_____	_____	_____
Slaughters on hand	_____	_____	_____
Weight of slaughters sold	_____	_____	_____
Finishing only:			
24 - Slaughters sold (total)	_____	_____	_____
Slaughters on hand (ave)	_____	_____	_____
Weight of feeders purchased	_____	_____	_____
Weight of slaughters sold	_____	_____	_____

Notes____

____

____

Farm Number________

Livestock and dairy operations (3 of 3)

Beef: Type of operation: ______ combined cow-calf/feedlot Oper.

_______Cow-calf operation ______ feedlot (finishing) operation

Breeds: Ave._%_ of _ herd

__________________ ____________

__________________ ____________

We are trying to determine the number of beef that are raised on your farm.

Ave # animals during yr.	_1993_	_1994_	"AVG "
31 - Bulls	______	______	______
32 - Cows	______	______	______
Cow-calf operation:			
33 - Calves sold (total)	______	______	______
Calves on hand	______	______	______
Avg. WEIGHT sale	______	______	______
Feedlot operation:			
34 - Feeders sold (total)	______	______	______
Feeders on hand	______	______	______
Avg. weight at purch	______	______	______
Avg. weight at sale	______	______	______
Calf to finish:(birth to slaughter)			
35 - Feeders sold (total)	______	______	______
Feeders on hand	______	______	______
Avg. weight at sale	______	______	______

IV. MANURE HANDLING; EXCLUDING APPLICATION

MANURE STORAGE:

1---No storage, daily scrape and haul ________

2---Unpaved lot__________

3---Paved lot_____________

4---Animal barn____________

20---HALF BARN HALF LOT

If you have a solid, Semi-solid ,or liquid storage what type?

5---Paved pad, covered________________

6---Paved pad, uncovered_______________

7---Drained storage, covered____________

8---Drained storage, uncovered____________

9---Storage building_____________

10--Pit under barn _______________

11--Above ground tank, concrete______________

12--Above ground tank, steel (Slurrystore)_____________

13--Unpaved pad, covered_____________

14--Unpaved pad, uncovered_____________

15--Outside earthen storage pit, covered_______________

16--Earthen storage pit, uncovered_______________

17--lagoon_____________

18--Poultry pit___________________

19--Compost system___________

IV. MANURE HANDLING; EXCLUDING APPLICATION ***HOG MANURE***
GENERAL DESCRIPTION:___________________________
List the manure collections in terms of livestock type to each system. Account for each system identified on page 6.

System 1: **Codes**________ **TiS**

20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (APPROX 0-50LB)
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS BOARS)
26--Mature Hogs(with young 0-20LB)

Conveyed_____

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months________
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LIQUID 2-SOLID)

Months________
SPREADING FREQUENCY:

SPREADER CAP:________

UNITS:________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

System 2: **Codes**________ **TiS**

20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 0-50LB)
22--Feederpig days (APPROX 0-50LB)
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS, BOARS)
26--Mature Hogs(with young 0-20LB)

Conveyed_____

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months________
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LIQUID 2-SOLID)

Months________
SPREADING FREQUENCY:

SPREADER CAP:________

UNITS:________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

System 3: **Codes**________ **TiS**

20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX 50LB)
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS, BOARS, REPLACE)
26--Mature Hogs(with young 0-20LB)

Conveyed_____

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months________
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LIQUID 2-SOLID)

Months________
SPREADING FREQUENCY:

SPREADER CAP:________

UNITS:________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

System 4: **Codes**________ **TiS**

20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX 50LB)
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS, BOARS)
26--Mature Hogs(with young 0-20LB)

Conveyed_____

1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months________
SYSTEM CAPACITY:

MANURE TYPE:_____
(-LIQUID 2-SOLID)

Months________
SPREADING FREQUENCY:

SPREADER CAP:________

UNITS:________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

System 5: **Codes**__________ **TiS** 20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS, BOARS,

26--Mature Hogs(with young 0-20LB)

Conveyed_____
50LB)
1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER
REPLACE)

Months________
SYSTEM CAPACITY:

MANURE TYPE:______
(-LIQUID 2-SOLID)

Months________
SPREADING FREQUENCY:

SPREADER CAP:_________

UNITS:_________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

System 6: **Codes**_________ **TiS** 20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS, BOARS)
26--Mature Hogs(with young 0-20LB)

Conveyed_____
50LB)
1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months________
SYSTEM CAPACITY:

MANURE TYPE:______
(-LIQUID 2-SOLID)

Months________
SPREADING FREQUENCY:

SPREADER CAP:_________

UNITS:_________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

System 7: **Codes**__________ **TiS** 20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS, BOARS,

26--Mature Hogs(with young 0-20LB)

Conveyed_____
50LB)
1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER
REPLACE)

Months________
SYSTEM CAPACITY:

MANURE TYPE:______
(-LIQUID 2-SOLID)

Months________
SPREADING FREQUENCY:

SPREADER CAP:_________

UNITS:_________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

System 8: **Codes**_________ **TiS** 20--Nursery (APPROX 10-20 LB)
21--GROWER(APPROX 20-50LB)
22--Feederpig days (UP TO APPROX
23--Feeder to Slaughter(50LB TO 240)
24--Birth to Slaughter(0-240LB)
25--Mature Hogs(SOWS, BOARS)
26--Mature Hogs(with young 0-20LB)

Conveyed_____
50LB)
1-NONE 2-GRAVITY 3-FLUSHED
4-PUMPED 5-HAULED 6-CONVEYER

Months________
SYSTEM CAPACITY:

MANURE TYPE:______
(-LIQUID 2-SOLID)

Months________
SPREADING FREQUENCY:

SPREADER CAP:_________

UNITS:_________
(GAL, BUSH, TON)

Animal Type	Number	Time in System or Months

Farm Number____________________

IV. MANURE HANDLING; EXCLUDING APPLICATION

MANURE HANDLING SYSTEM GENERAL QUESTIONS

GIVEN DAILY SCRAPE AND HAUL

If you were to build a manure handling system, liquid or solid, what type would it be?____________________

What do you think the total cost would be?____________________

Is cost sharing available in your area?____________________

If so, do you know how much you could get on the system you identified above?____________________

Compared to your daily scrape and haul system, how do you think the system identified above would affect the amount of the following nutrients provided by your manure? Think now about the amounts made available to crops. (Example answers: no change, 50%, more, etc.)

N __________

P __________

K __________

Why haven't you installed it?____________________

____

Will you, or under what conditions would you reconsider?

____

____

Notes____________________

____

Farm Number____________________

IV. MANURE HANDLING

MANURE HANDLING SYSTEM GENERAL QUESTIONS

GIVEN LONG TERM STORAGE

When did you install last system____________________

Previous system____________________

Approximate installation cost (whole system) ____________________

Labor savings or loss compared to previous system ____________________

____

Other savings or extra costs from previous system ____________________

____

Motivating Factor____________________

____

Second thoughts____________________

Notes____________________

____

V. OFF FARM MANURE PURCHASE; GENERAL QUESTIONS

System number_______ (101 or more)

If you purchase, or receive free, manure:

Animal Type	Number	Time in System or Months
______	______	______
______	______	______
______	______	______

OR

AMOUNT RECEIVED_________ BUSHELS, GALLONS TONS____________

IS THIS TOTAL AMOUNT OR PER ACRE?___________

What form is it? (1-liquid 2-solid)_______________

On what basis do you purchase it? (Volume, analysis, etc)

____

ANALYSIS INCLUDE ON ANALYSIS PAGE

On what basis do you pay for it?_________________________

Total cost________________ Cost per unit_________________________

Does the cost above include: Unit description?___________

-transport to your farm?___________ application?___________

How do you determine and monitor app._____________________________

Total tons of manure purchased:________

Do you sell or give away any manure? How much?

Tons________ Gallons__________ Bushels__________

OR

Animal TYPE_______ NUMBER______ TiS Code_______

Farm Number____________________

VII. CROPS AND ROTATIONS general rotation pattern:

____

Do you part. in ASCS Comm. Prog.?_________ Does it affect your rotations?_______________________________________

How many acres were planted to the following crops

Year	1993	1994	"AVG"
Acres in:			
POTATOES	______	______	______
CRP/ RIM	______	______	______
CORN	______	______	______
Soybeans	______	______	______
Small grains	______	______	______
Alfalfa	______	______	______
Pasture	______	______	______
Edible beans: type____	______	______	______
Sunflowers	______	______	______
Sugar beets	______	______	______
Peas	______	______	______
Sweet corn	______	______	______
Buildings\roads	______	______	______
Other__________	______	______	______
Other__________	______	______	______
__________	______	______	______
Total (AS IN SEC.I)	______	______	______

IRRIGATION QUESTIONS: **SOIL MOISTURE CONTENT:**
WHAT METHODS DO YOU USE TO DETERMINE SOIL MOISTURE CONTENT FOR IRRIGATION SCHEDULING. RATE TOP THREE IN ORDER OF IMPORTANCE:

____ CROP CONSULTANT
____ CHECKBOOK METHOD
____ FEEL METHOD (HAND)
____ SOIL PROBING (MECHANICAL)
____ TENSIOMETERS OR THEIR MOISTURE SEEKING DEVICES
____ PLANT APPEARANCE
____ INFRA-RED OR OTHER PLANT STRESS MEASUREMENTS
____ ESTIMATE BY EXPERIENCE
____ NEED FOR FERTILIZER
____ OTHER

AMOUNT TO APPLY:
WHICH OF THE FOLLOWING FACTORS DO YOU USE TO DETERMINE HOW MUCH IRRIGATION WATER PER APPLICATION TO APPLY?

____ LONG TERM WEATHER FORECASTS (3 OR MORE DAYS)
____ SHORT TERM WEATHER FORECASTS (0-3 DAYS)
____ EVAPORATION TRANSPORTATION
____ CROP CONSULTANT
____ CROP ROOTING ZONE
____ EXPERIENCE
____ NEED FOR FERTILIZER
____ SET WATER APPLICATION
____ REPORTED VALUES OF CROP WATER USE
____ PAST RAINFALL
____ POWER COMPANY LOAD LIMITS AND OTHER CHARGES
____ EVAPORATION PAN
____ PREDOMINANT SOIL TYPE FOR EACH FIELD
____ OTHER ________________________________
____ SOIL WATER DEPLETION LIMITS

SOIL DEPLETION CHECK ONE:
IRRIGATION IS DONE WHEN DEPLETION OF AVAILABLE WATER IS BETWEEN:
___ 10% - 30% ___ 30% - 50% ___ MORE THAN 50%
AND/OR: ___ STAGE OF CROP ___ SIZE OF PIVOT (TIME TO COVER FIELD)

IS SOIL WATER RETURNED TO:
___ FIELD CAPACITY ___ LESS THAN CAPACITY

IRRIGATION:

HOW DO YOU ESTIMATE THE ANNUAL WATER USE OR FLOW RATE OF YOUR SYSTEMS:

____ ELECTRIC COMPANY FORMULAS
____ RAIN GAUGES
____ ELECTROMAGNETIC METERS
____ DIFFERENTIAL FLOW METERS
____ ULTRASONIC FLOW METER
____ CROP CONSULTANT ESTIMATES
____ OTHER OR DON'T ________________________________

WHAT IS THE RATE (GALLONS PER MINUTE)? ____________________

DO YOU USE A COMPUTER TO MAKE IRR DECISIONS? ____________

WHAT TYPE OF PROGRAM? (WISP, CHECKBOOK, ETC) ____________

WHAT IS THE AVERAGE MOISTURE HOLDING CAPACITY OF YOUR SOIL? (TOP 24")

____ LESS THAN 1/2"
____ 1/2 TO 1"
____ 1 - 1 1/2"
____ 1 1/2 - 2"
____ MORE THAN 2"

DO YOU MONITOR RAINFALL

AT YOUR FARM? ______

IRRIGATION SITE? ______

IS IRRIGATION WEATHER FEEDBACK SUCH AS MINIMUM AND MAXIMUM TEMPS OR NET SOLAR RADIATION AVAILABLE TO YOU? ____ DO YOU USE IT? ____

WHERE IS IT AVAILABLE FROM: ________________________

COMMENTS? ________________________

Farm Number____________________

VIII. IDENTIFICATION OF MANAGEMENT AREAS.

We are attempting to analyze crop management differences across your farm. Before considering any management applications and irrigation more specifically, we need to identify the areas you manage differently. We are primarily interested in areas which are irrigated AND/OR to which you apply commercial N, follow legumes in rotation (soybeans or alfalfa [2 years]), or manure. All combinations of these four practices, plus differences in crops define separate management areas. For example, irrigated cont. corn w/ scrape and haul manure differs from an identical area except that it receives liquid manure.(Differences in physical characteristics may also determine management areas. The map of the farm would be good here.){Identify the most productive field with in NOTES column.}

1-Conventional 2-Conservation 3-Notill 4-Ridgetill

AREA #	TYPE		CROPS		ACRES	TILL?	MAN?	NOTES
94 - 93 - 92								

AREA #	TYPE		CROPS		ACRES	TILL?	MAN?	NOTES
94 - 93 - 92								

IDENTIFY most productive field with a checkmark.

Farm Number________

Did you have analysis done on your manure? _____

System Number___ Date of last test?________

Percentage?___ Per gallon?___ Per ton?___

Avail N____ Total N____ P205____ K20____

System Number___ Date of last test?________

Percentage?___ Per gallon?___ Per ton?___

Avail N____ Total N____ P205____ K20____

System Number___ Date of last test?________

Percentage?___ Per gallon?___ Per ton?___

Avail N____ Total N____ P205____ K20____

System Number___ Date of last test?________

Percentage?___ Per gallon?___ Per ton?___

Avail N____ Total N____ P205____ K20____System Number___

Test lab where analysis is done______________________________

Cost of analysis____________________________________

If you have not had a recent test, Why?___________

1--Too Expensive 2--Not Accurate 3--No Time 4--other

Notes____

____

Farm Number___________

MANURE APPLICATIONS:(2 of 2)

List the destination of the manure from:(Systems, barns, and lots)
Include EACH application as a separate entry.
(Don't forget to include application of off farm manure produced off the farm, regardless of who applies it). Amount Per Acre column is for manure applied where amount applied per acre is known. Measure column
1--bushel per acre 2--gallon per acre 3--tons per acre

<--------------THIS------------------->OR<------THIS---------->

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________
____	______	____	________	______	________

NOTE: Be sure that you have accounted for 100% of the collected manure from each manure handling system. You also need to make sure that all manured areas are accounted for here!!! Don't forget
off farm manure!!!!

List below any manure system collected but not available and

why:____

____

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

SYSTEM ______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

SYSTEM _______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

SYSTEM _______

AREA	AMOUNT	DATE	APP METH	APA	MEASURE

FARM NUMBER____________

DEFINITION PAGE FOR COMMERCIAL NITROGEN

Growth stages can be:

- 1-Fall
- 2-Spring preplant
- 3-Starter (with the planter)(PRE-EMERGENCE FOR HERB)
- 4-Emergence
- 5-TUBER
- 6-HILLING
- 7-Other

Type of nitrogen applied *DEFINE STARTERS*

11-Anhydrous ammonia   12-urea
13-U.A.N. (solutions or liquid nit.) 14-Ammonium nitrate (34%)
15-Liquid starter   16-Dry mix (urea or unknown)
17-Other   18-AMMONIUM SULFATE (21%)
19- CALCIUM NITRATE (16%)   20-M A P (11-52-0)
21- D A P (18-46-0)   21-TRIPLE PHOSPHATE (0-46-0)

Form of nitrogen:

21-gas (NH3)
22-liquid
23-dry
24-other

Application method: Define method of planter app. from bellow!!

(SAME FOR MANURE) 31-injected   32-broadcast
33-incorporated (include broadcast fields worked in 2 days)
34-banded (side dress)   35-irr   36-other
37-Knifed in (man only)   38-Swept in (man only)

XI. COMMERCIAL FERTILIZER APPLICATIONS (N, P, and K).**careful**

MGMT AREA #__________ POTATO TYPE__________

Application_#	1	2	3	4
App. date				
Growth stage				
FERT TYPE (ANHYD, UREA, ECT)				
Fert. form (dry, liquid, gas)				
Analysis(% N,P,K)*ASK IF %*				
Lbs fert. (FOR %)				
OR Lbs. nut. **(ACTUAL)**				
App. method(broad,inj,etc)				
Fert. Cost (mat. or nut./lb.)				
Custom App Cost				
Appl. time (if self app, hrs)				

Last soil test in this area?__________

By who?Crop consultant,SELF?:__________

Lab:__________

WHO MAKES DECISIONS ON FERTILIZER AMOUNTS?__________

WHERE IS THE RECOMMENDATION NUMBERS FROM (U/M, FERT CO. , ETC) ?

____

SOIL TEST RESULTS:

Organic matter %:____ or low/med/high____ or derived number:_____

Nitrate soil test: ppm:_____ pounds per acre:_______

pH:____ Olson test: ppm:_____ pounds per acre:_______

Bray 1 (low bray): ppm:_____ pounds per acre:_______

Potassium (K2o):____

How often do you test each field?____

XI.COMMERCIAL FERTILIZER APPLICATIONS (N, P, and K)

HAVE YOU HAD YOUR WELL TESTED FOR NITRATES?__________

DO YOU USE THAT INFORMATION FOR NITROGEN CREDITING (FERTILIZER RECOMMENDATIONS)?__________

ARE YOU USING PETIOLE ANALYSIS?__________

IF YES, IS IT DONE IN A LAB OR IS IT A FIELD TEST?__________

HAVE YOU DONE A CALIBER TEST OR AN IRRIGATION UNIFORMITY CALIBRATION TEST FOR WATER UNIFORMITY IN THE PAST?__________

WHEN? __________

COMMENTS:__________

____

____

____

FARM NUMBER____________________ XII. Yield info

POTATOES (by management area)

AREA	TYPE	HARVEST DATE	1993	AVG	YIELD GOAL	1994	COVER CROP

FARM NUMBER____________________

THANK YOU FOR YOUR TIME AND EFFORT. AS I SUMMARIZE THE RESULTS, AN ADDITIONAL QUESTION, OR THE NEED FOR SOME CLARIFICATION MAY ARISE. IF SO, I HOPE I CAN GIVE YOU A CALL TO GET THE ADDITIONAL INFORMATION.

AS INDICATED BEFORE, WE WILL BE CONTACTING YOU LATER THIS YEAR FOR INFO REGARDING YOUR 1992 YIELDS AND IRRIGATION APPLICATIONS.

[WHAT ABOUT MANURE TESTING]!!!!!!!!

THANKS AGAIN!!!!!!!!!!!!!!!!!!!!!!!!

CHECKLIST FOR COMPLETENESS AND CONSISTENCY. Take a minute to check these out before the farmer is freed.

1. Total acreage on the crop summary (p. 14) must agree with total land on p. 1 ._____

2. Acreages of mgmt areas (p. 15-16) must be reconciled with crop summary (p. 14)._____

3. All management areas (p.15-16) must be supported by appropriate supporting info re irrigation, manure apps and commercial N apps (p 20-22)._____

4. Manure applications (p. 19) must account for all collected manure (p. 6-10)._____

7. All cash crops acres must be accounted for on the yield sheet (p. 23)._____

B. Title of objective: Refine diagnostic criteria to predict in-season nitrogen needs for irrigated potatoes

B.1. Activity: Field experiments will be conducted using various N treatment regimes to define petiole sap nitrate critical values suitable for predicting nitrogen fertilizer needs.

B.1.a. Context within the project: Conventional N management for potatoes on irrigated soils consists of N fertilizer applications at planting, emergence, hilling, and post-hilling. One rational approach for managing N to reduce nitrate leaching would be to limit applications prior to hilling when plants are small and then base post-hilling N applications on a diagnostic N test. The emphasis of this objective is to calibrate the petiole sap nitrate test to more accurately predict N needs of irrigated potatoes during the growing season.

B.1.b. Methods: A two-year field experiment using the Russet Burbank cultivar (the most common cultivar used on irrigated soils in Minnesota) will be conducted to calibrate the nitrate sap test for diagnostic purposes. Data generated under this objective will be used to define critical sap nitrate concentrations that will serve as an indicator of N needs in potatoes. Treatments will consist of a 0 N control and eight N management strategies based on N applications at various times through the growing season. The main calibration experiment will be conducted at the Sand Plain Research Farm in Becker, MN, a site near an area where large acreages of irrigated potatoes are grown. Additional experiments to validate the sap test will also be conducted at Staples Irrigation Center and a grower site at Park Rapids MN (see objective C.1.). For these smaller experiments, a typical grower rate of nitrogen application (270 kg N/A) and a treatment based on the sap test will be tested. Planting, emergence, and hilling N applications will be made with an ammonium based fertilizer. All post-hilling applications will be made at two week intervals with urea-ammonium nitrate solution. A 34 kg ha^{-1} rate of N is typical of that used by growers when supplemental N is applied posthilling and will be used in the current experiment when additional nitrogen is required. Each plot will consist of six, 9-meter rows consisting of two border rows, two sample rows, and two harvest rows. The experimental design will be a randomized complete block with 4 replications. The checkbook method will be used to schedule irrigation. At harvest, tubers will be separated and graded according to marketability. Yield data will be subjected to standard analysis of variance procedures.

Nitrogen uptake by the potato crop: Whole plant samples (roots, tubers, and shoots) will be collected from each plot at hilling, and then at 16-day intervals until harvest (5 collection dates). Samples will be dried and ground for subsequent total N determination using the Kjeldahl-salicylic acid method.

Sap/petiole sampling: Sap will be collected at weekly intervals from 15-20 of the most recently expanded petioles in each plot starting two weeks after emergence until the first week in August (about 10 sampling dates). Petioles collected for the sap test will be placed in plastic bags in a cooler, transported back to the lab, and sap will be extracted with a Hach sap press. Expressed sap will be frozen until all nitrate determinations can be made (preliminary studies have shown that freezing does not change the nitrate concentrations in the sap). The reason for not determining the nitrate directly in the field for this objective is the large number of samples being collected and number of instruments being used for determinations which makes it impractical. An additional 15-20 petioles will also be collected to determine N status based on the traditional method of analysis (dry weight basis). Petioles sampled for the traditional method will be dried at 60C and then ground to pass through a 30 mesh screen.

Nitrate determination/calibration: Nitrate in sap will be determined using the Hach electrode, the Horiba/Cardy electrode and the Wescan N analyzer. The comparison with the Wescan N analyzer will be used because this technique is not sensitive to the same interferences often observed with electrodes and, therefore, will be a check for accuracy. Sap will be diluted with an aluminum sulfate solution for the electrode nitrate determinations and with water for the Wescan determinations. For the dried petiole analysis, nitrate from ground samples will be extracted with deionized water and then determined using the Wescan analyzer. Two approaches will be taken to calibrate the sap test. Since critical values of nitrate for deficiency, optimum, and excess have been established for nitrate in petioles using traditional procedures (dry weight basis), the first approach will be to correlate traditional petiole nitrate test and the quick nitrate sap tests. From this correlation, sap nitrate critical values can be determined based on the conventional analysis. This approach will be compared with establishing critical sap nitrate-N levels based on correlations of petiole nitrate sap concentrations with potato yield and N uptake at specific growth stages.

B.1.c. Materials: Potato seed, fertilizer, equipment, nitrate electrodes, laboratory reagents/supplies.
B.1.d. Budget: $59,500, **Balance:** $0

B.1.e. Timeline	7/93	1/94	6/94	1/95	6/95
Establish field plots	xxxx		xxxx		

Collect petiole samples xxxx   xxxx
Sample analysis   xxxxx   xxxx
Develop critical sap nitrate levelsxxxxxxxxxxxxx

B.1.f. Status: Two nitrogen (N) management studies on irrigated potatoes were conducted during 1993 and 1994 at the Sand Plain Research Farm in Becker, MN to evaluate the effects of various N management strategies on N use and nitrate movement under irrigated Russet Burbank potatoes. A second objective was to calibrate a quick petiole nitrate sap test for determining nitrogen status of the crop and predicting nitrogen needs.

In 1993, tuber yield increased with increasing N rate up to 240 lb N/A, with the greatest increase occurring between the 0 and 120 lb N/A rate. At equivalent N rates, use of post-hilling N applications tended to result in larger tubers compared to applying all the N up to hilling. Leaching of N was related more to rate of N applied than timing of application. Final tuber yields with urea as the N source were similar to those with ammonium nitrate as the N source, although early plant growth with ammonium nitrate was greater than with urea. The early response to ammonium nitrate may have been due to cooler temperatures, which may have retarded conversion of urea to ammonium and nitrate. Petiole nitrate increased with increasing N rate and with post-hilling N applications. Petiole nitrate decreased through the season at a faster rate with treatments that did not involve post-hilling N application compared to those that did. The correlation between petiole sap nitrate and nitrate in petioles based on dry weight was highly significant with an r-squared of 0.92. The slope and intercept of the line was similar to the results from 1991 and 1992, suggesting that the tentative sap critical values based on previous year's calibration used to predict N needs were appropriate.

Overall, 1994 was a low leaching year. However, insect pressure from Colorado potato beetle and aphids caused early dieback and limited yields. Tuber yield increased with increasing N rate up to 120 lb N/A with little response above this rate. The relatively low response to N above 120 lb N/A may have been due to lack of N leaching and poor late season growth due to insect/disease pressure. At equivalent N rates, there were no significant differences in tuber yield or quality due to timing of N application. Hollow heart increased with increasing N rate, but was not affected by post-hilling N application. Higher concentrations of nitrate in soil water at the 4 ft depth were found in the row compared to between the row for most treatments. Leaching of N was related more to rate of N applied than timing of application. Final tuber yields with urea as the N source were similar to those with ammonium nitrate as the N source. Petiole nitrate increased with increasing N rate and with post-hilling N applications. The quick tests used reflected the changes in petiole nitrate with N treatment. Use of petiole testing in 1994 predicted an N response in the 120 and 160 lb N/A treatments, yet a response to additional N was not observed. As mentioned above, the lack of response was probably due to early dieback. The results from 1994 indicate that an integrated approach to N management needs to be taken. If plants are dying of insect and disease pressure then, additional N may not be beneficial even if a need is indicated by the petiole test.

The overall results from this calibration study have helped to improve diagnostic criteria for determining N needs for irrigated Russet Burbank potato. Calibration studies still need to be conducted for other varieties, but it should be noted that Russet Burbank is the dominant variety grown in Minnesota (about 50 to 60% of the acreage). Approximate sap nitrate-N sufficiency ranges for Russet Burbank based on the calibration study are: 1300-1600 ppm for initial vegetative growth/tuber initiation; 900 to 1200 ppm for tuber growth/bulking; and 550 to 800 ppm for tuber bulking/maturation. These diagnostic criteria have been incorporated into Nitrogen Best Management Practices for irrigated potatoes. The overall effects of N fertigation on potato production and nitrate leaching in irrigated potatoes are evaluated under Objective C.

Detailed Report - Objective B

NITROGEN MANAGEMENT FOR IRRIGATED POTATOES: EFFECTS OF NITROGEN TIMING AND SOURCE ON SOIL NITRATE MOVEMENT AND PETIOLE SAP NITRATE INTERPRETATION - 1993

Carl Rosen, Mohamed Errebhi, John Moncrief, Satish Gupta, H. H. Cheng, and Dave Birong[1]

ABSTRACT: The third year of a four year study was conducted at the Sand Plain Research Farm in Becker, MN to evaluate the effects of various N management strategies on nitrogen use and nitrate movement under irrigated potatoes. A second objective was to calibrate a quick petiole nitrate sap test for determining nitrogen status of the crop and predicting nitrogen needs. Tuber yield increased with increasing N rate up to 240 lb N/A, with the greatest increase occurring between the 0 and 120 lb N/A rate. At equivalent N rates, use of post-hilling N applications tended to result in larger tubers compared to applying all the N up to hilling. Leaching of N was related more to rate of N applied than timing of application. Final tuber yields with urea as the N source were similar to those with ammonium nitrate as the N source, although early plant growth with ammonium nitrate was greater than with urea. The early response to ammonium nitrate may have been due to cooler temperatures, which may have inhibited conversion of ammonium to nitrate when urea was used.

Potatoes grown on sandy soils under irrigation are usually provided with high rates of nitrogen (N) to promote growth and yield. Concern about ground water quality, however, has raised questions about the fate of N applied to potatoes on irrigated soils. In part, this concern is due to the fact that potatoes have a relatively shallow root system, yet require relatively high rates of N to maintain profitable production. Proper N management is critical to minimize losses of N from the root zone and maintain yields. The objectives of this study were to characterize the pattern of soil nitrate-N movement during irrigated potato production under defined nitrogen management regimes and to develop diagnostic tools for quick and accurate prediction of the need for N by potato during the growing season. The results presented below are the third year of a four year study.

EXPERIMENTAL PROCEDURES

The experiment was conducted in Becker, MN at the Sand Plain Research Farm on a Hubbard loamy sand soil. The previous crop was rye. Selected soil chemical properties prior to planting were as follows (0-6"): pH, 6.8; organic matter, 2.5%; phosphorus, 31 ppm; potassium, 95 ppm; sulfur, 1 ppm. Residual nitrate-N in the top 3 feet of soil was 13 lb/A. Prior to planting, 200 lbs/A 0-0-22 and 200 lbs/A 0-0-60 were broadcast and incorporated. Russet Burbank "B" size potatoes were planted April 20, 1993 at a spacing of 36" between rows and 10" within the row. Phosphate (0-46-0) and potash (0-0-60) fertilizer were applied in the band at planting at a rate of 80 lb P_2O_5/A and 200 lb K_2O/A to all plots. The fertilizer was banded 3" to each side and 2" below the tuber. Individual plot size consisted of six, 30 ft rows. The middle two rows (3 and 4) were harvest rows and rows 2 and 5 were sample rows. Ten treatments were tested to evaluate the effects of various N management practices on potato productivity, N use/uptake, soil nitrate movement, and petiole N status during the course of the season.

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The 10 specific treatments were as follows:

	N Application Rate (lb N/A)						
N Source	Planting	Emergence	Hilling	Post-Hilling	Post-Hilling	Post-Hilling	Post-Hilling
1) Control	0	0	0	0	0	0	0
2) Urea	40	100	100	0	0	0	0
3) Urea	20	70	70	20	20	20	20
4) Urea	20	70	70	0	0	0	0
5) Ammonium nitrate	40	100	100	0	0	0	0
6) Ammonium nitrate	20	70	70	20	20	20	20
7) Ammonium nitrate	20	70	70	0	0	0	0
8) Ammonium nitrate	40	40	40	0	0	0	0
9) Ammonium nitrate	40	40	40	0	20	20	20
10) Ammonium nitrate	40	40	40	20	20	20	20

Nitrogen applied at planting was banded with the P and K fertilizer. Nitrogen applied at emergence (May 26) was banded 1" deep and 8" from each side of the plant. At hilling (June 11), the N fertilizer was sidedressed on the surface on either side of the plant and then incorporated during the hilling process. Post-hilling applications to treatments #3, 6, and 10 were applied on June 18, July 2, July 13 and July 19. Applications were made by broadcasting 50% ammonium nitrate and 50% urea over the plot by hand and then irrigating in. Post-hilling applications to treatment #9 were June 25, July 2, and July 13.

The experimental design was a randomized complete block with 4 replications. Rainfall was supplemented with overhead irrigation to supply water needs according to the checkbook method. Rainfall during the growing season totaled 31 inches and was supplemented with 5.9 inches of irrigation. The nitrate-N concentration in the irrigation water averaged 8 to 10 ppm. Given that 5.9 inches of irrigation were applied, approximately 14 lbs of additional N was provided with the irrigation water. Figure 1 shows the weekly precipitation (rainfall + irrigation) through the growing season.

Recently matured potato leaves (4th leaf from the growing terminal) were collected every

10-14 days starting one day before hilling for nitrate-N determinations. Thirty leaves were collected from each plot. Leaflets were removed, half of the petioles were crushed with a Hach press, and the remaining petioles were dried in an oven at 140°F. The expressed sap was immediately frozen until analyses could be performed.

Two instruments designed for quick tests were compared: the Hach nitrate electrode and the Horiba/Cardy nitrate electrode. In addition to the quick test procedures, nitrate in sap and nitrate in dried petioles were determined conductimetrically using a Wescan nitrogen analyzer.

Specific methods for analyses were as follows:

Hach Test - The instrument was calibrated using two standard solutions. One ml of expressed sap was mixed with 25 ml of 0.075 molar aluminum sulfate solution. The electrode was immersed in the solution and a reading was recorded. The reading was related to concentration of nitrate-N in the sap by using a standard curve.

Horiba/Cardy Test - The instrument was calibrated using two standard solutions, 34 and 450 ppm nitrate-N. A few drops of nondiluted sap were placed on the electrode membrane and a direct reading of nitrate-N was recorded.

Wescan Sap Test - The instrument was calibrated using five standard solutions. One ml of expressed sap was mixed with water to a volume of 100 ml in a volumetric flask. Diluted solutions were run through the instrument and the reading recorded was related to the concentration of nitrate-N in the sap using a standard curve.

Wescan Petiole Nitrate Test - The instrumental set up was the same as for the sap test. Dried petioles were ground and 0.1 g of ground tissue was weighed and mixed with 20 ml of water. Samples were shaken for 30 minutes and then filtered. The reading recorded was related to concentration of nitrate-N in dried tissue using a standard curve.

Nitrate-N was determined in soil samples collected one week after harvest. Samples consisted of 3 cores from an individual plot taken to a depth of 3 feet at 1 foot increments. All samples were brought back to the lab and air dried. Nitrate and ammonium were extracted with 2 N KCl using a 5 g to 25 ml soil:extractant ratio. Results are expressed as pounds of nitrate-N using the convention ppm X 2 = lb/A for a 6" furrow slice. Bulk density of each sampling depth was not determined, so lb/A values should be considered approximate.

Suction tubes, consisting of a porous ceramic cup and 1.5" diameter PVC tubes, were installed one week after planting in one of the sample rows and between the rows at the 4.5 ft depth. Nitrate-N in soil water was determined in samples collected every 1-2 weeks from the suction tubes.

Three plants from the other sample row from each plot were harvested on June 22 to determine the effects of the N treatments on initial growth. Samples were dried, weighed, and ground. Total N was determined using the salicylic Kjeldahl method. At harvest, vines were cut and weighed 5 days prior to harvest. Potatoes were mechanically harvested on September 15. Subsamples of vines and tubers were collected to determine dry matter and N accumulation. Tubers were evaluated for hollow heart and specific gravity was determined.

RESULTS

Rainfall and Soil Nitrate Movement. Weekly precipitation over the course of the season is presented in Figure 1. Leaching events (> 2" rainfall/day) only occurred three times, at 58, 111, and 130 days after planting. Seasonal nitrate-N concentrations in soil water extracted with the suction tubes at the 4.5′ depth in and between the row for each treatment are shown in Figures 2 to 11. Although nitrate-N in the soil water was measured, these numbers do not represent the concentration of nitrate in the ground water. Nor do they indicate the amount of nitrate lost to the ground water. The only way these data can be interpreted is in a more qualitative sense. That is, a higher peak for one treatment compared to another at a given time, indicates that losses of nitrate were relatively greater, but does not indicate how much greater. These data, therefore, can be used to determine which treatments minimized nitrate movement out of the root zone. The control treatment, where no fertilizer N was applied, had nitrate-N concentrations that increased to 20 ppm during the first 12 weeks of the growing season (Figure 2). This nitrate originated from organic matter mineralization that occurs following tillage.

Differences in nitrate movement due to N sources (urea vs. ammonium nitrate) were not that apparent (Figs. 2, 3, 4 vs. 5, 6, 7). Possibly due to the fact that leaching was not a problem until later in the growing season. Higher concentrations of nitrate were generally found in the row compared to between the row with little difference between nonpost-hilling and post-hilling applications at equivalent rates. Exceptions were post-hilling treatments 9 and 10, where high in row nitrate levels were found (Figs 10 and 11). Reasons for this higher level for these treatments are unclear. Higher rates of N generally resulted in higher nitrate concentrations in and between the row (Figs. 4, 7, 8 vs. 2, 3, 6, 7, 10) regardless of timing. By the end of the season after harvest, nitrate-N in soil water tended to increase for all treatments. Even though winter rye was planted, nitrate may have already moved beyond where the rye roots could take it up.

One week after harvest, extractable soil nitrate was higher in the N fertilized plots compared to the 0 N control, but there was little difference in soil nitrate concentrations among the N fertilized treatments (Table 1).

Tuber Yield, Specific Gravity, Hollow Heart, and Vine Yield. The effects of the various

N treatments on tuber yield, specific gravity, hollow heart, and vine yield are presented in Table 3. Total yield increased with N rate with most of the yield increase occurring between the control treatment and 120 lb N/A (treatment 8). The 7-14 oz tuber size increased significantly with N rate. Vine yield also increased with increasing N rate. Specific gravity of tubers from the control treatment was generally higher than in those receiving N. Specific gravity decreased with increasing N rate. At similar N rates and timing of application, there was little difference between urea and ammonium nitrate on vine and tuber and vine yields. Specific gravity was similar for the urea and ammonium nitrate treatments when applied at equal rates. The post-hilling N application treatments 3 and 6 resulted in equal total yields compared to 240 lbs N/A applied through hilling (treatments 2 and 5). Post-hilling treatments resulted in greater yield of 7 - 14 oz potatoes compared to all the N applied up to hilling. Specific gravity was not affected by post-hilling N applications. Additional N after hilling resulted in larger tubers compared to the lower rates applied up to hilling; however, specific gravity was lower with the post-hilling N applications. Hollow heart tended to increase with increasing N rate but was not significantly affected by timing of N application.

Treatment Effects on Early Plant Growth. Increasing nitrogen rate resulted in more tubers per plant, greater dry matter accumulation, and higher N concentrations in plants sampled one week after hilling (Table 2). Ammonium nitrate did result in more tubers, and greater dry matter accumulation in vines and roots, and higher tissue N concentrations compared to urea. These results suggest that ammonium nitrate may be beneficial for early harvested potatoes. As expected all N applied up to hilling resulted in higher tissue N concentrations than post-hilling treatments since all the post-hilling N applications had not yet been applied.

Dry Matter and Nitrogen Accumulation. Dry matter and N accumulation, as well as concentrations of N in vines and tubers at harvest, are presented in Table 4. As expected, dry weight, N concentrations in vines and tubers, and N accumulation increased with increasing N rate. At equivalent N rates, post-hilling N applications increased N concentrations in vines and tubers compared to all N applied up to hilling, but did not significantly increase total N uptake. Dry matter accumulation was slightly lower with post-hilling N applications, which accounted for the lack of an effect on n uptake despite higher N concentrations with post-hilling applications. Nitrogen uptake and dry matter production were not affected by N source (urea vs. ammonium nitrate).

Nitrate-N Concentrations in Petiole Samples. The N status of the plant (sampled every 10-14 days starting one day before hilling), as measured by conventional petiole analysis and sap analysis, is presented in Table 5. On all sampling dates, nitrate on a dry weight or sap basis increased with increasing N rate. On the first sampling date, petiole nitrate concentrations were lower with the urea N source than with ammonium nitrate. After this date, petiole nitrate levels were not generally affected by N source. The lower level of petiole nitrate early may have been due to cooler weather inhibiting conversion of ammonium to nitrate for the urea N source. Differences in petiole nitrate due to post-hilling applications were not apparent until July 21. Nitrate concentrations were slightly higher with the Cardy meter compared to the Hach. The Wescan method gave slightly lower readings than both electrodes.

SUMMARY

The 1993 season at Becker was a moderate year for nitrate leaching. Nitrogen rate significantly affected nitrate losses under irrigated potatoes. Greatest losses were observed as N rate increased. Post-hilling applications of N also reduced N losses compared to similar rates of N applied before hilling. Potato yield was primarily affected by N rate. The greatest yield increase was obtained between the 0 and 120 lb N/A increment. Petiole sap nitrate tests using portable nitrate electrodes appear to have promise for determining N status of the crop; however, using the N status to predict N needs will require additional research to evaluate timing and rates of post-hilling application to maximize yield.

Table 1. Effect of nitrogen treatments on soil nitrate-N in the top 3 ft. (pounds per acre ± one standard deviation) at the end of the growing season. Becker, MN - 1993.

	Treatment N source	N timing	0 to 1 foot	1 to 2 foot	2 to 3 foot	Field total
			Pounds per acre			
1.	Control	(0 N/A)	3.47 ± 2.06	3.28 ± 1.77	1.11 ± 0.41	7.86 ± 3.55
2.	(46-0-0)	(40,100,100)[1]	9.98 ± 4.28	7.91 ± 6.21	1.68 ± 1.13	19.57 ± 10.49
3.	(46-0-0)	(20,70,70)+80[2]	9.80 ± 4.01	8.33 ± 2.62	1.32 ± 0.63	21.95 ± 2.76
4.	(46-0-0)	(20,70,70)	8.02 ± 5.02	8.17 ± 1.85	1.58 ± 0.30	17.77 ± 6.08
5.	(34-0-0)	(40,100,100)	12.31 ± 5.25	6.77 ± 3.95	1.03 ± 0.68	20.11 ± 9.05
6.	(34-0-0)	(20,70,70)+80[2]	9.82 ± 5.96	9.33 ± 4.35	1.74 ± 0.58	20.89 ± 10.21
7.	(34-0-0)	(20,70,70)	10.27 ± 4.95	11.46 ± 3.48	2.07 ± 0.64	23.80 ± 6.92
8.	(34-0-0)	(40,40,40)	7.50 ± 5.65	6.26 ± 3.34	1.89 ± 0.77	15.65 ± 9.31
9.	(34-0-0)	(40,40,40)+60[3]	7.10 ± 4.08	5.81 ± 2.98	1.35 ± 0.76	14.26 ± 6.06
10.	(34-0-0)	(40,40,40)+80[2]	12.21 ± 5.41	7.73 ± 3.52	2.26 ± 1.20	22.20 ± 9.41

[1] = Planting, emergence, and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis.

Table 2. Effect of nitrogen treatments on fresh weight of vines, tubers, and hollow heart. Becker, MN - 1993.

	Treatment N source	N timing	Vines Tons/A	Knobs	<3 oz	3-7 oz	7-14 oz	>14 oz	Total	Specific Gravity	Hollow Heart-% incidence
				Fresh weight (cwt/A)							
1.	Control	(0 N/A)	0.78	11.9	16.9	132.8	65.1	4.4	231.2	1.0874	2.0
2.	(46-0-0)	(40,100,100)[1]	3.42	59.0	28.3	144.9	167.9	55.2	455.2	1.0825	10.0
3.	(46-0-0)	(20,70,70)+80[2]	5.00	35.4	22.4	143.8	196.3	53.8	451.8	1.0831	14.7
4.	(46-0-0)	(20,70,70)	1.91	63.3	28.0	156.5	160.6	28.0	436.5	1.0873	17.0
5.	(34-0-0)	(40,100,100)	4.88	63.2	28.9	148.3	192.6	42.2	475.3	1.0828	12.0
6.	(34-0-0)	(20,70,70)+80[2]	5.54	36.6	26.0	139.9	200.7	55.7	458.8	1.0812	10.0
7.	(34-0-0)	(20,70,70)	1.51	66.3	31.6	153.1	169.6	21.8	442.5	1.0850	12.0
8.	(34-0-0)	(40,40,40)	0.76	61.6	26.7	175.0	144.5	10.0	417.8	1.0885	6.0
9.	(34-0-0)	(40,40,40)+60[3]	2.76	51.6	33.5	153.9	175.0	32.4	446.4	1.0843	15.0
10.	(34-0-0)	(40,40,40)+80[2]	3.16	47.0	28.9	155.9	163.4	53.1	448.3	1.0810	5.0
Significance			**	**	NS	*	**	**	**	**	NS
BLSD (0.05)			1.44	20.1	--	27.1	28.6	16.8	24.0	0.0030	--
Contrasts											
Lin Rate N (1, 5, 7, 8)			**	**	*	NS	**	**	**	**	*
Quad Rate N (1, 5, 7, 8)			*	**	NS	*	**	NS	**	NS	NS
Post-hilling (2, 5) vs (3, 6)			*	**	NS	NS	++	NS	NS	NS	NS
(2, 3, 4) vs (5, 6, 7)			NS	NS	NS	NS	NS	NS	NS	NS	NS
Treatment 3 vs 4			**	**	NS	NS	*	**	NS	NS	NS
Treatment 6 vs 7			**	**	NS	NS	*	**	NS	*	NS
Treatment 9 vs 10			NS	**	NS	NS	NS	*	NS	*	++

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant; ++, *, ** = significant at 10%, 5% and 1%, respectively.

Table 3. Effect of nitrogen treatments on root and vine dry matter, tuber number and dry matter; sampled June 22, 1993 - Becker, MN.

	Treatment N source	N timing	Tubers -#/plant-	dry matter Tuber (g/plant)	Vine	Root	Total	N concentration Tuber (% N)	Vine	Root
1.	Control	(0 N/A)	3.83	2.2	8.3	1.8	12.3	1.48	3.01	1.49
2.	(46-0-0)	(40,100,100)[1]	5.25	7.0	31.5	2.8	41.3	1.98	4.88	2.41
3.	(46-0-0)	(20,70,70)+80[2]	5.55	5.8	32.4	2.8	41.0	2.17	5.22	2.58
4.	(46-0-0)	(20,70,70)	5.83	5.5	28.7	2.4	36.6	1.92	4.88	2.36
5.	(34-0-0)	(40,100,100)	6.33	5.2	41.7	3.2	50.0	2.00	5.25	2.40
6.	(34-0-0)	(20,70,70)+80[2]	7.08	6.3	35.4	3.3	45.1	2.29	5.67	2.70
7.	(34-0-0)	(20,70,70)	8.33	8.3	35.1	3.2	47.4	1.80	5.06	2.43
8.	(34-0-0)	(40,40,40)	5.66	5.7	38.4	3.2	47.3	1.94	4.63	2.43
9.	(34-0-0)	(40,40,40)+60[3]	6.25	7.3	35.1	3.0	45.3	1.87	4.58	2.19
10.	(34-0-0)	(40,40,40)+80[2]	8.33	9.7	38.9	3.3	51.8	2.17	5.26	2.34
Significance			NS	NS	**	**	**	**	**	**
BLSD (0.05)			--	--	5.4	0.6	7.5	0.25	0.20	0.22
Contrasts										
Lin Rate N (1, 5, 7, 8)			*	NS	**	**	**	**	**	**
Quad Rate N (1, 5, 7, 8)			NS	NS	**	*	**	**	**	**
Post-hilling (2, 5) vs (3, 6)			NS	NS	NS	NS	NS	**	**	*
(2, 3, 4) vs (5, 6, 7)			++	NS	**	**	**	NS	**	NS
Treatment 3 vs 4			NS	NS	NS	NS	NS	*	**	++
Treatment 6 vs 7			NS	NS	NS	NS	NS	**	**	*
Treatment 9 vs 10			NS	NS	NS	NS	NS	*	**	NS

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant, ++, *, ** = significant at 10%, 5%, and 1%, respectively.

Table 4. Effect of nitrogen on N content, concentration, and dry matter production. Becker, MN

	Treatment N source	N timing	Nitrogen content Vines (lbs/A)	Tubers	Total	N concentration Vine (% N)	Tubers	Dry matter Vines (Tons/A)	Tubers	Total
1.	Control	(0 N/A)	4.7	51.1	55.8	1.28	1.01	0.18	2.52	2.70
2.	(46-0-0)	(40,100,100)[1]	25.6	131.3	157.0	1.42	1.37	0.88	4.83	5.70
3.	(46-0-0)	(20,70,70)+80[2]	26.2	138.4	164.6	1.85	1.53	0.71	4.50	5.22
4.	(46-0-0)	(20,70,70)	13.7	112.4	126.2	1.03	1.16	0.67	4.84	5.51
5.	(34-0-0)	(40,100,100)	22.8	137.6	160.4	1.58	1.40	0.73	4.94	5.66
6.	(34-0-0)	(20,70,70)+80[2]	31.0	143.8	174.8	2.05	1.50	0.76	4.81	5.58
7.	(34-0-0)	(20,70,70)	16.6	119.5	136.2	1.18	1.24	0.71	4.78	5.49
8.	(34-0-0)	(40,40,40)	8.2	94.7	102.9	0.80	1.02	0.52	4.67	5.19
9.	(34-0-0)	(40,40,40)+60[3]	17.8	123.2	141.0	1.54	1.31	0.58	4.73	5.31
10.	(34-0-0)	(40,40,40)+80[2]	24.6	141.6	166.2	1.73	1.52	0.71	4.68	5.39
Significance			**	**	**	**	**	**	**	**
BLSD (0.05)			8.7	16.6	18.4	0.28	0.18	0.26	0.37	0.42
Contrasts										
Lin Rate N (1, 5, 7, 8)			**	**	**	++	**	**	**	**
Quad Rate N (1, 5, 7, 8)			NS	**	**	NS	NS	NS	**	**
Post-hilling (2, 5) vs (3, 6)			NS	NS	NS	**	*	NS	NS	++
(2, 3, 4) vs (5, 6, 7)			NS	NS	NS	++	NS	NS	NS	NS
Treatment 3 vs 4			**	**	**	**	**	NS	NS	NS
Treatment 6 vs 7			**	*	**	**	**	NS	NS	NS
Treatment 9 vs 10			NS	*	*	NS	*	NS	NS	NS

[1] = Planting, emerge d hilling respectively. [2] = Four post-hilling applicatio 0 pounds N/A each, based on sap analys = Three post-hilling applications at 20 pounds N/A each, d on sap analysis. NS = Nonsignificant, .., *, ** = significant at 10%, 5%, and 1%, respectively.

Table 5. Effect of nit n treatments on nitrate-N concentration in potato petiole / weight basis) and nitrate tration in petiole sap, as determined by various procedu Becker, MN.

Treatment			Date							
			June 10				June 24			
	N source	N timing	dry weight Petiole-N	sap Horiba	sap Hach	sap Wescan	dry weight Petiole-N	sap Horiba	sap Hach	sap Wescan
			ppm NO_3-N							
1.	Control	(0 N/A)	1676	211	159	122	1035	160	100	88
2.	(46-0-0)	(40,100,100)[1]	21779	1438	1260	1135	20688	1650	1288	1295
3.	(46-0-0)	(20,70,70)+80[2]	20844	1325	1209	1110	21662	1625	1308	1324
4.	(46-0-0)	(20,70,70)	22260	1538	1369	1187	20579	1600	1324	1241
5.	(34-0-0)	(40,100,100)	24332	1575	1425	1301	24584	1650	1261	1295
6.	(34-0-0)	(20,70,70)+80[2]	25143	1688	1469	1376	23198	1625	1346	1376
7.	(34-0-0)	(20,70,70)	24814	1625	1490	1380	21414	1600	1233	1249
8.	(34-0-0)	(40,40,40)	24106	1563	1376	1261	14265	1225	931	936
9.	(34-0-0)	(40,40,40)+60[3]	22730	1550	1303	1205	15054	1200	956	1089
10.	(34-0-0)	(40,40,40)+80[2]	24274	1538	1360	1255	19149	1525	1209	1204
Significance			**	**	**	**	**	**	**	**
BLSD (0.05)			1884	217	128	86	1817	156	124	126
Contrasts										
Lin Rate N (1, 5, 7, 8)			**	**	**	**	**	**	**	**
Quad Rate N (1, 5, 7, 8)			**	**	**	**	**	**	**	**
Post-hilling (2, 5) vs (3, 6)			NS	NS	NS	NS	NS	NS	NS	NS
(2, 3, 4) vs (5, 6, 7)			**	**	**	**	**	NS	NS	NS
Treatment 3 vs 4			NS	++	*	NS	NS	NS	NS	NS
Treatment 6 vs 7			NS	NS	NS	NS	++	NS	NS	++
Treatment 9 vs 10			NS	NS	NS	NS	**	**	**	NS

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant, ++, *, ** = significant at 10%, 5%, and 1%, respectively.

Table 5 cont. Effect of nitrogen treatments on nitrate-N concentration in potato petioles (dry weight basis) and nitrate concentration in petiole sap, as determined by various procedures. Becker, MN.

Treatment			Date							
			July 8				July 21			
	N source	N timing	dry weight Petiole-N	sap Horiba	sap Hach	sap Wescan	dry weight Petiole-N	sap Horiba	sap Hach	sap Wescan
			ppm NO_3-N							
1.	Control	(0 N/A)	215	73	49	37	995	158	115	93
2.	(46-0-0)	(40,100,100)[1]	21451	1388	1295	1276	17670	1425	1356	1339
3.	(46-0-0)	(20,70,70)+80[2]	22951	1438	1385	1362	22257	1575	1475	1442
4.	(46-0-0)	(20,70,70)	17099	1200	1117	1099	4367	458	383	365
5.	(34-0-0)	(40,100,100)	22120	1488	1306	1342	17216	1375	1235	1217
6.	(34-0-0)	(20,70,70)+80[2]	21320	1375	1286	1235	18624	1375	1369	1359
7.	(34-0-0)	(20,70,70)	15678	1150	1067	1033	3853	503	431	401
8.	(34-0-0)	(40,40,40)	5986	550	458	434	384	136	67	44
9.	(34-0-0)	(40,40,40)+60[3]	15401	1275	1134	1099	15864	1350	1249	1223
10.	(34-0-0)	(40,40,40)+80[2]	16466	1175	1079	1032	13931	1300	1171	1128
Significance			**	**	**	**	**	**	**	**
BLSD (0.05)			1768	153	127	127	1867	164	121	120
Contrasts										
Lin Rate N (1, 5, 7, 8)			**	**	**	**	**	**	**	**
Quad Rate N (1, 5, 7, 8)			**	**	**	**	**	**	**	**
Post-hilling (2, 5) vs (3, 6)			NS	NS	NS	NS	**	NS	*	*
(2, 3, 4) vs (5, 6, 7)			NS	NS	NS	NS	*	NS	NS	NS
Treatment 3 vs 4			**	**	**	**	**	**	**	**
Treatment 6 vs 7			**	*	**	**	**	**	**	**
Treatment 9 vs 10			NS	NS	NS	NS	++	NS	NS	NS

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant, ++, *, ** = significant at 10%, 5%, and 1%, respectively.

Table 5 cont. t of nitrogen treatments on nitrate-N concentration in petioles (dry weight basis) trate concentration in petiole sap, as determined by vario procedures. Becker, MN.

Treatment			Date							
			August 4				August 18			
	N source	N timing	dry weight Petiole-N	sap Horiba	sap Hach	sap Wescan	dry weight Petiole-N	sap Horiba	sap Hach	sap Wescan
			ppm NO_3-N							
1.	Control	(0 N/A)	67	94	44	12	20	58	37	3
2.	(46-0-0)	(40,100,100)[1]	9704	851	737	704	2486	250	202	182
3.	(46-0-0)	(20,70,70)+80[2]	15053	1263	1174	1120	5660	604	501	522
4.	(46-0-0)	(20,70,70)	1836	334	246	227	168	78	55	23
5.	(34-0-0)	(40,100,100)	8487	891	782	749	2587	245	196	182
6.	(34-0-0)	(20,70,70)+80[2]	15929	1188	1071	1046	5563	530	431	441
7.	(34-0-0)	(20,70,70)	1510	270	205	168	209	78	57	26
8.	(34-0-0)	(40,40,40)	161	101	55	18	151	66	40	10
9.	(34-0-0)	(40,40,40)+60[3]	9181	828	775	732	1474	205	171	154
10.	(34-0-0)	(40,40,40)+80[2]	16651	1150	1053	1033	3386	378	302	299
Significance			**	**	**	**	**	**	**	**
BLSD (0.05)			2080	106	96	98	1571	115	98	108
Contrasts										
Lin Rate N (1, 5, 7, 8)			**	**	**	**	**	**	**	**
Quad Rate N (1, 5, 7, 8)			**	**	**	**	++	++	NS	++
Post-hilling (2, 5) vs (3, 6)			**	**	**	**	**	**	**	**
(2, 3, 4) vs (5, 6, 7)			NS	NS	NS	NS	NS	NS	NS	NS
Treatment 3 vs 4			**	**	**	**	**	**	**	**
Treatment 6 vs 7			**	**	**	**	**	**	**	**
Treatment 9 vs 10			**	**	**	**	*	**	*	*

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant, ++, *, ** = significant at 10%, 5%, and 1%, respectively.

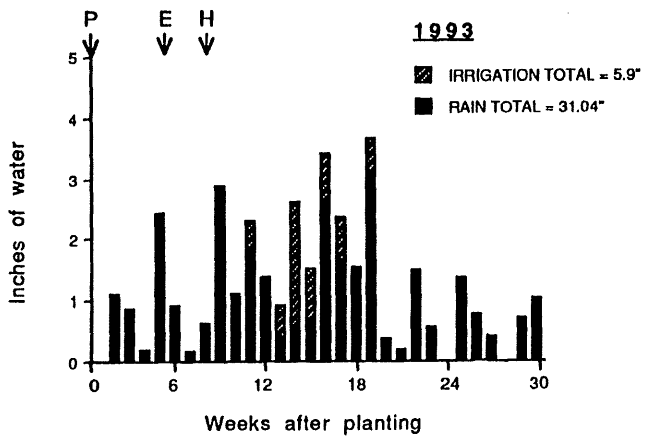

Figure 1. Rainfall and irrigation at Becker, MN during the 1993 growing season. P, H and E = planting, emergence and hilling, respectively.

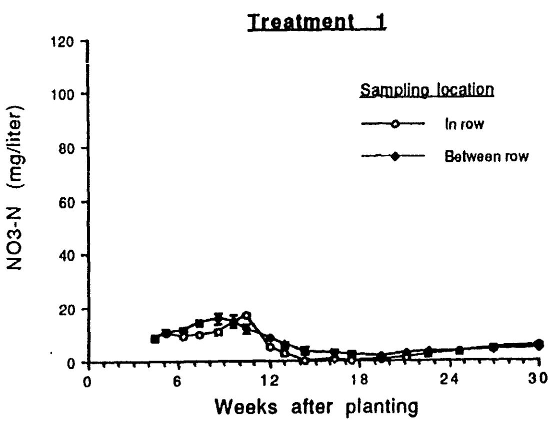

Figure 2. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: no nitrogen. Error bar represents SE of the mean.

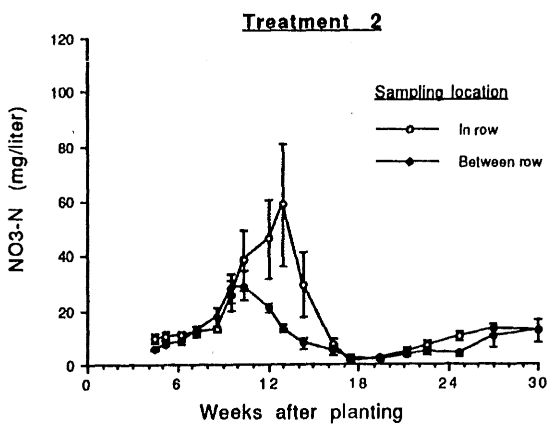

Figure 3. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: 40 lb N/A at planting, 100 lb at emergence and hilling (46-0-0). Error bars represent SE of the mean.

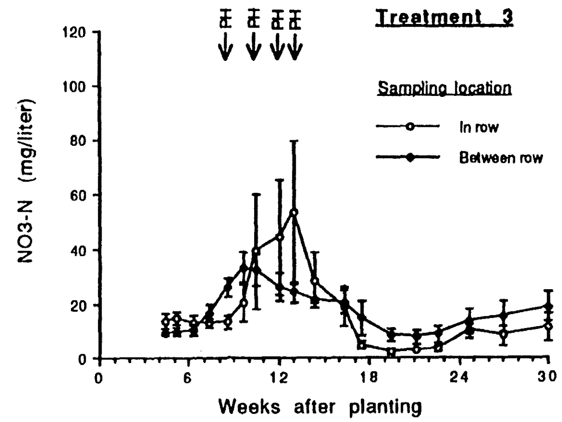

Figure 4. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: 20 lb N/A at planting, 70 lb at emergence and hilling, plus 4 post-hilling applications at 20 lb N/A each (46-0-0). Error bars represent SE of the mean. PH = post-hilling application.

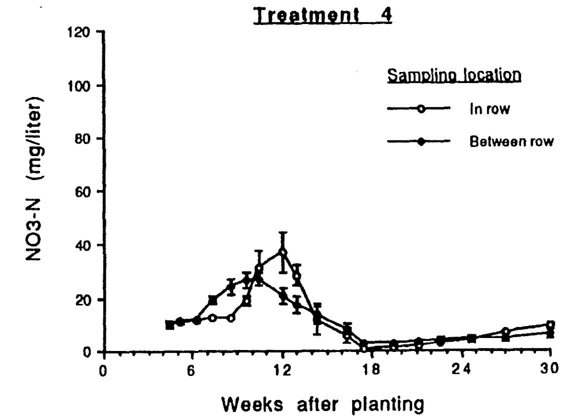

Figure 5. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: 20 lb N/A at planting and 70 lb at emergence and hilling (46-0-0). Error bars represent SE of the mean.

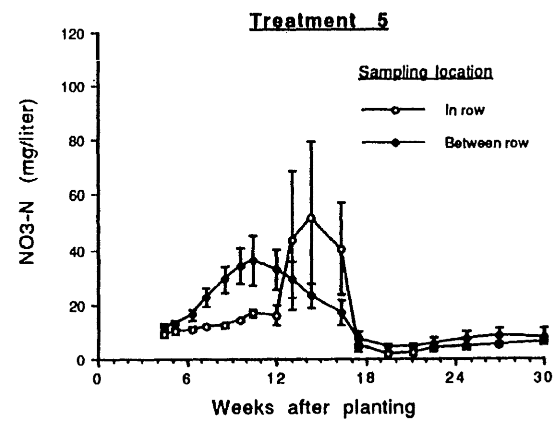

Figure 6. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: 40 lb N/A at planting, 100 lb at emergence and hilling (34-0-0). Error bars represent SE of the mean.

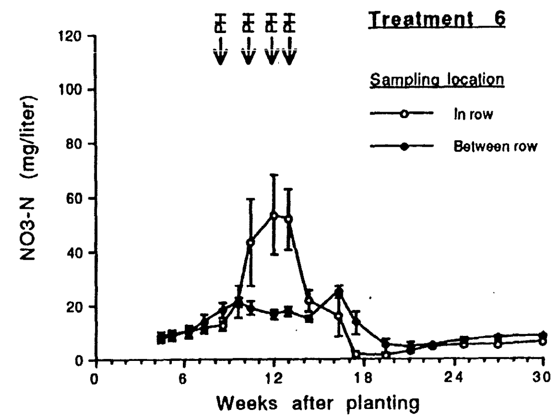

Figure 7. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: 20 lb N/A at planting, 70 lb at emergence and hilling, plus 4 post-hilling applications at 20 lb N/A each (34-0-0). Error b[illegible] represent SE of the mean. PH = post[illegible] application.

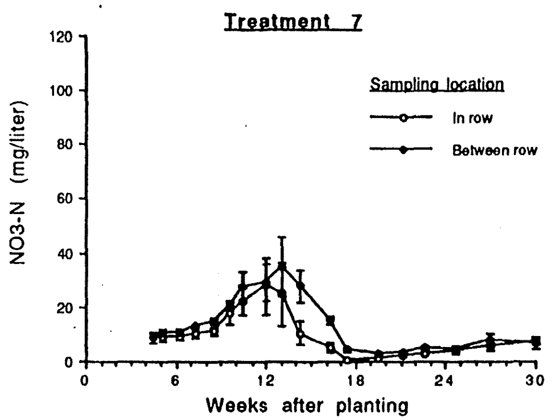

Figure 8. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: 20 lb N/A at planting and 70 lb at emergence and hilling (34-0-0). Error bars represent SE of the mean.

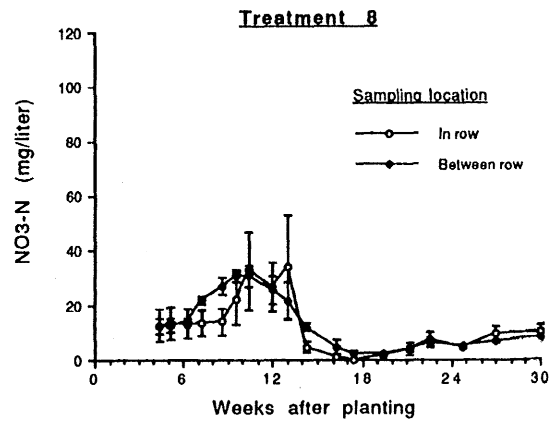

Figure 9. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: 40 lb N/A at planting, emergence and hilling (34-0-0). Error bars represent SE of the mean.

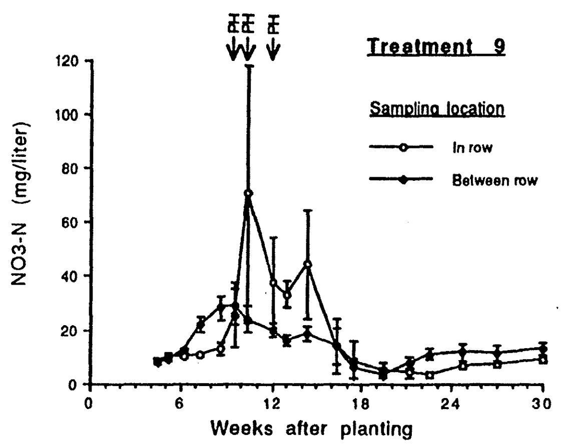

Figure 10. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: 40 lb N/A at planting, emergence and hilling, plus three post hilling applications at 20 lb N/A each (34-0-0). Error bars represent SE of the mean. PH = post-hilling application.

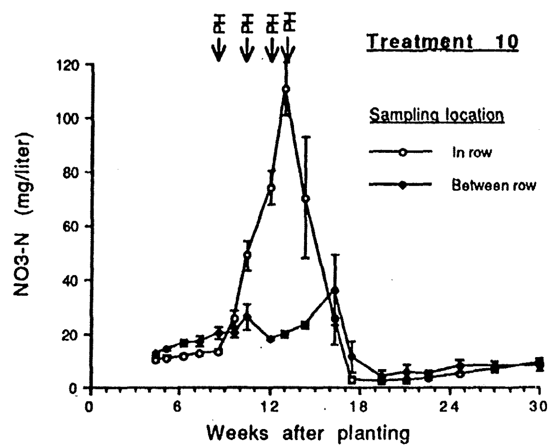

Figure 11. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1993 growing season. Nitrogen application rate: 40 lb N/A at planting, emergence and hilling, plus four post-hilling applications at 20 lb N/A each (34-0-0). Error bars represent SE of the PH = post-hilling application.

NITROGEN MANAGEMENT FOR IRRIGATED POTATOES: EFFECTS OF NITROGEN TIMING AND SOURCE ON SOIL NITRATE MOVEMENT AND PETIOLE SAP NITRATE INTERPRETATION - 1994[1]

Carl Rosen, Mohamed Errebhi, John Moncrief, Satish Gupta, H. H. Cheng, and Dave Birong[2]

ABSTRACT: The fourth year of a four year study was conducted at the Sand Plain Research Farm in Becker, MN to evaluate the effects of various N management strategies on N use and nitrate movement under irrigated potatoes. A second objective was to continue with calibration of a quick petiole nitrate sap test for determining N status of the crop and predicting nitrogen needs. Overall, 1994 was a low leaching year. Insect pressure due to Colorado potato beetle and aphids caused early dieback and limited yields. Tuber yield increased with increasing N rate, with the greatest increase occurring between the 0 and 120 lb N/A rate. Relatively low response to N above this rate may have been due to lack of N leaching and poor late season growth due to insect pressure. At equivalent N rates, there were no significant differences in tuber yield or quality due to timing of N application. Hollow heart increased with increasing N rate, but was not affected by post-hilling N application. Higher concentrations of nitrate in soil water at the 4 ft depth were found in the row compared to between the row for most treatments. Leaching of N was related more to rate of N applied than timing of application. Final tuber yields with urea as the N source were similar to those with ammonium nitrate as the N source. Petiole nitrate increased with increasing N rate and with post-hilling N applications. The quick tests used reflected the changes in petiole nitrate with N treatment. Sap nitrate concentrations determined with the Cardy meter tended to be 50 to 100 ppm higher than readings from the Hach or Wescan instruments.

Potatoes grown on sandy soils under irrigation are usually provided with high rates of nitrogen (N) to promote growth and yield. Concern about ground water quality, however, has raised questions about the fate of N applied to potatoes on irrigated soils. In part, this concern is due to the fact that potatoes have a relatively shallow root system, yet require relatively high rates of N to maintain profitable production. Proper N management is critical to minimize losses of N from the root zone and maintain yields. The objectives of this study were to characterize the pattern of soil nitrate-N movement during irrigated potato production under defined nitrogen management regimes and to develop diagnostic tools for quick and accurate prediction of the need for N by potato during the growing season. The results presented below are the fourth year of a four year study.

[1]Associate Professor, Graduate Research Assistant, Extension Soil Scientist, Professor, Professor, and Junior Scientist, respectively, Department of Soil Science.

EXPERIMENTAL PROCEDURES

The experiment was conducted in Becker, MN at the Sand Plain Research Farm on a Hubbard loamy sand soil. The previous crop was rye. Selected soil chemical properties prior to planting were as follows (0-6"): pH, 6.9; organic matter, 2.5%; phosphorus, 40 ppm; potassium, 123 ppm; sulfur, 2 ppm. Residual nitrate-N in the top 3 feet of soil was 14 lb/A. Prior to planting, 200 lbs/A 0-0-22 and 210 lbs/A 0-0-60 were broadcast and incorporated. Russet Burbank "B" size potatoes were planted April 14, 1994 at a spacing of 36" between rows and 10" within the row. Phosphate (0-46-0) and potash (0-0-60) fertilizer were applied in the band at planting at a rate of 80 lb P_2O_5/A and 200 lb K_2O/A to all plots. The fertilizer was banded 3" to each side and 2" below the tuber. Individual plot size consisted of six, 30 ft rows. The middle two rows (3 and 4) were harvest rows and rows 2 and 5 were sample rows. Ten treatments were tested to evaluate the effects of various N management practices on potato productivity, N use/uptake, soil nitrate movement, and petiole N status during the course of the season. The 10 specific treatments were as follows:

	N Application Rate (lb N/A)						
N Source	Planting	Emergence	Hilling	Post-Hilling	Post-Hilling	Post-Hilling	Post-Hilling
1) Control	0	0	0	0	0	0	0
2) Urea	40	100	100	0	0	0	0
3) Urea	20	70	70	20	20	20	20
4) Urea	20	70	70	0	0	0	0
5) Ammonium nitrate	40	100	100	0	0	0	0
6) Ammonium nitrate	20	70	70	20	20	20	20
7) Ammonium nitrate	20	70	70	0	0	0	0
8) Ammonium nitrate	40	40	40	0	0	0	0
9) Ammonium nitrate	40	40	40	0	20	20	20
10) Ammonium nitrate	40	40	40	20	20	20	20

Nitrogen applied at planting was banded with the P and K fertilizer. Nitrogen applied at emergence (May 19) was banded 1" deep and 8" from each side of the plant. At hilling (June 7), the N fertilizer was sidedressed on the surface on either side of the plant and then incorporated during the hilling process. Post-hilling applications to treatments #3, 6, and 10 were applied on June 15, June 23, June 28 and July 6. Applications were made by broadcasting 50% ammonium nitrate and 50% urea over the plot by hand and then irrigating in. Post-hilling applications to treatment #9 were June 15, June 28, and July 12.

The experimental design was a randomized complete block with 4 replications. Rainfall was supplemented with overhead irrigation to supply water needs according to the checkbook method. Rainfall during the growing season totaled 22 inches and was supplemented with 9.5 inches of irrigation. The nitrate-N concentration in the irrigation water averaged 8 to 10 ppm. Given that 9.5 inches of irrigation were applied, approximately 20 lbs of additional N was provided with the irrigation water. Figure 1 shows the weekly precipitation (rainfall + irrigation) through the growing season.

Recently matured potato leaves (4th leaf from the growing terminal) were collected every 10-14 days starting one day before hilling for nitrate-N determinations. Thirty leaves were collected from each plot. Leaflets were removed, half of the petioles were crushed with a Hach press, and the remaining petioles were dried in an oven at 140°F. The expressed sap was immediately frozen until analyses could be performed.

Two instruments designed for quick tests were compared: the Hach nitrate electrode and the Horiba/Cardy nitrate electrode. In addition to the quick test procedures, nitrate in sap and nitrate in dried petioles were determined conductimetrically using a Wescan nitrogen analyzer.

Specific methods for analyses were as follows:

Hach Test - The instrument was calibrated using two standard solutions. One ml of expressed sap was mixed with 25 ml of 0.075 molar aluminum sulfate solution. The electrode was immersed in the solution and a reading was recorded. The reading was related to concentration of nitrate-N in the sap by using a standard curve.

Horiba/Cardy Test - The instrument was calibrated using two standard solutions, 34 and 450 ppm nitrate-N. A few drops of nondiluted sap were placed on the electrode membrane and a direct reading of nitrate-N was recorded.

Wescan Sap Test - The instrument was calibrated using five standard solutions. One ml of expressed sap was mixed with water to a volume of 100 ml in a volumetric flask. Diluted solutions were run through the instrument and the reading recorded was related to the concentration of nitrate-N in the sap using a standard curve.

Wescan Petiole Nitrate Test - The instrumental set up was the same as for the sap test. Dried petioles were ground and 0.1 g of ground tissue was weighed and mixed with 20 ml of water. Samples were shaken for 30 minutes and then filtered. The reading recorded was related to concentration of nitrate-N in dried tissue using a standard curve.

Nitrate-N was determined in soil samples collected one week after harvest. Samples consisted of 3 cores from an individual plot taken to a depth of 3 feet at 1 foot increments. All samples were brought back to the lab and air dried. Nitrate and ammonium were extracted with 2 N KCl using a 5 g to 25 ml soil:extractant ratio. Results are expressed as pounds of nitrate-N using the convention ppm X 2 = lb/A for a 6" furrow slice. Bulk density of each sampling depth was not determined, so lb/A values should be considered approximate.

Suction tubes, consisting of a porous ceramic cup and 1.5" diameter PVC tubes, were installed one week after planting in one of the sample rows and between the rows at the 4 ft depth. Nitrate-N in soil water was determined in samples collected every 1-2 weeks from the suction tubes.

Three plants from the other sample row from each plot were harvested on June 20 to determine the effects of the N treatments on initial growth. Samples were dried, weighed, and ground. Total N was determined using the salicylic Kjeldahl method. At harvest, vines were cut and weighed 8 days prior to harvest. Potatoes were mechanically harvested on September 15. Subsamples of vines and tubers were collected to determine dry matter and N accumulation. Tubers were evaluated for hollow heart and specific gravity was determined.

RESULTS

Rainfall and Soil Nitrate Movement. Weekly precipitation over the course of the season is presented in Figure 1. Major leaching events (> 2" rainfall/day) did not occur during the 1994 growing season. Seasonal nitrate-N concentrations in soil water extracted with the suction tubes at the 4.5' depth in and between the row for each treatment are shown in Figures 2 to 11. Although nitrate-N in the soil water was measured, these numbers do not represent the concentration of nitrate in the ground water. Nor do they indicate the amount of nitrate lost to the ground water. The only way these data can be interpreted is in a more qualitative sense. That is, a higher peak for one treatment compared to another at a given time, indicates that losses of nitrate were relatively greater, but does not indicate how much greater. These data, therefore, can be used to determine which treatments minimized nitrate movement out of the root zone.
The control treatment, where no fertilizer N was applied, had nitrate-N concentrations that increased to 20 ppm during the first 12 weeks of the growing season, decreased and then increased after harvest (Figure 2). The nitrate detected in this treatment originated from organic matter mineralization that occurred following tillage operations (planting, cultivation, and harvest).

As expected, nitrate concentrations below the root zone increased with increasing N rate with concentrations in the row generally greater than concentrations between the row (Figures 4, 7, 8 vs. 2, 3, 6, 7, 10). Nitrate concentrations at equivalent N rates when urea was used as the N source tended to be less than those when ammonium nitrate was used as the N source (Figs. 2, 3, 4 vs. 5, 6, 7). When urea was used as the N source there was little difference between nonpost-hilling and post-hilling applications at equivalent rates. However, with ammonium nitrate as the N source, nitrate concentrations in the row were lower with post-hilling N applications. Higher than expected nitrate concentrations were detected in post-hilling treatments where lower rates of N were applied through hilling (treatments 9 and 10, Figures 10 and 11). Reasons for the higher levels in these treatments are unclear.

One week after harvest, extractable soil nitrate was higher in the N fertilized plots compared to the 0 N control, but there was little difference in residual soil nitrate concentrations among the N fertilized treatments (Table 1).

Treatment Effects on Early Plant Growth. Increasing nitrogen rate had no effect on tuber number, but did result in greater dry matter accumulation, and higher N concentrations in plants sampled one week after hilling (Table 2). Source of N (ammonium nitrate vs urea) had no effect on tuber number, dry matter accumulation, or tissue N concentrations. All N applied up to hilling resulted in greater dry matter accumulation and tuber number compared to post-hilling N treatments. Reduced N at planting, emergence, and hilling resulted in smaller plant growth early in the season.

Tuber Yield, Specific Gravity, Hollow Heart, and Vine Yield. The effects of the various N treatments on tuber yield, specific gravity, hollow heart, and vine yield are presented in Table 3. Total yield increased with N rate with most of the yield increase occurring between the control treatment and 120 lb N/A (treatment 8) with little increase in yield between 160 and 240 lb N/A. The 7-14 oz tuber size increased significantly with N rate. Reasons for the apparent lack of N response may have been due to the fact that 1) leaching losses were not that high, and 2) the crop died back early as a result of an uncontrollable outbreak of Colorado potato beetle and aphids. The early dieback may have limited the use of N at late in the season. Vine yield tended to increase with increasing N rate. Specific gravity of tubers from the control treatment was generally higher than in those receiving N. Specific gravity decreased with increasing N rate. At similar N rates and timing of application, there was little difference between urea and ammonium nitrate on vine and tuber yields. Specific gravity was similar for the urea and ammonium nitrate treatments. The post-hilling N application, treatments 3 and 6, resulted in equal tuber yields compared to 240 lbs N/A applied through hilling (treatments 2 and 5). At equivalent N rates, vine yield was greater with post-hilling N applications. Specific gravity was not affected by post-hilling N applications. Additional N after hilling resulted in larger tubers compared to the lower rates applied up to hilling. Hollow heart tended to increase with increasing N rate but was not consistently affected by timing of N application.

Dry Matter and Nitrogen Accumulation. Dry matter and N accumulation, as well as concentrations of N in vines and tubers at harvest, are presented in Table 4. As expected, dry weight, N concentrations in vines and tubers, and N accumulation increased with increasing N rate. At equivalent N rates, post-hilling N applications increased N concentrations in vines and vine N content compared to all N applied up to hilling, but did not significantly affect tuber N. Dry matter accumulation was not affected by post-hilling N applications. Total N uptake and dry matter production were not affected by N source (urea vs. ammonium nitrate); although, N concentrations in vines tended to be higher with ammonium nitrate as the N source.

Nitrate-N Concentrations in Petiole Samples. The N status of the plant (sampled every 10-14 days starting one day before hilling), as measured by conventional petiole analysis and sap analysis, is presented in Table 5. On all sampling dates, nitrate-N concentrations on a dry weight or sap basis increased with increasing N rate. On some sampling dates, petiole nitrate concentrations were lower with urea as the N source than with ammonium nitrate. Differences were generally small, but in some instances may affect the interpretation. Differences in petiole nitrate due to post-hilling applications were not apparent until July 11. Sap nitrate-N concentrations determined with the Cardy meter were 50 to 100 ppm higher than the those determined with the Hach or Wescan instruments. On some sampling dates Cardy meter readings were 200-300 ppm higher. Reasons for these differences are not clear and are currently being investigated further.

SUMMARY

The 1994 season at Becker was a low year for nitrate leaching. Increasing N rate significantly increased nitrate concentrations below the root zone. Because 1994 was a low leaching year, post-hilling applications of N had minimal effects on nitrate losses compared to similar rates of N applied before hilling. Potato yield was primarily affected by N rate. The greatest yield increase was obtained between the 0 and 120 lb N/A increment. Insects control was a problem in 1994. The early dieback caused by insect damage may have limited the response to N fertilizer. Clearly, an integrated approach to managing N fertilizer is needed that includes pest management. Petiole sap nitrate tests using portable nitrate electrodes have promise for determining N status of the crop.

Table 1. Effect of nitrogen treatments on soil nitrate-N in the top 3 ft. (pounds per acre ± one standard deviation) at the end of the growing season. Becker, MN - 1994.

	Treatment N source	N timing	0 to 1 foot	1 to 2 foot	2 to 3 foot	Field total
			-------	Pounds per acre	-------	
1.	Control	(0 N/A)	12.95 ± 3.58	3.69 ± 1.21	2.06 ± 0.48	18.69 ± 4.46
2.	(46-0-0)	(40,100,100)[1]	30.06 ± 9.44	6.21 ± 2.86	2.00 ± 0.83	38.27 ± 10.69
3.	(46-0-0)	(20,70,70)+80[2]	32.09 ± 14.25	4.71 ± 1.43	1.61 ± 0.46	38.41 ± 15.27
4.	(46-0-0)	(20,70,70)	19.28 ± 6.24	12.92 ± 13.02	3.09 ± 1.23	35.29 ± 8.55
5.	(34-0-0)	(40,100,100)	26.71 ± 6.31	6.72 ± 3.37	2.36 ± 1.88	35.79 ± 9.69
6.	(34-0-0)	(20,70,70)+80[2]	37.35 ± 17.01	7.59 ± 1.80	2.61 ± 1.15	47.55 ± 19.77
7.	(34-0-0)	(20,70,70)	18.55 ± 4.90	5.75 ± 2.74	2.01 ± 0.68	26.31 ± 8.10
8.	(34-0-0)	(40,40,40)	20.31 ± 2.24	6.30 ± 2.55	2.52 ± 0.59	29.13 ± 3.03
9.	(34-0-0)	(40,40,40)+60[3]	28.98 ± 8.47	6.60 ± 1.83	2.77 ± 1.84	38.36 ± 11.71
10.	(34-0-0)	(40,40,40)+80[2]	28.45 ± 5.24	7.02 ± 1.11	2.74 ± 1.34	38.21 ± 5.36

[1] = Planting, emergence, and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis.

Table 2. Effect of nitrogen treatments on fresh weight of vines, tubers, and hollow heart - Becker, MN - 1994.

	Treatment N source	N timing	Vines	Knobs	<3 oz	3-7 oz	7-14 oz	>14 oz	Total	Specific Gravity	Hollow Heart-%
			Fresh weight								
			Tons/A	cwt/A							incidence
1.	Control	(0 N/A)	0.51	13.2	84.1	183.7	45.6	3.7	330.3	1.0871	8.0
2.	(46-0-0)	(40,100,100)[1]	2.67	48.8	56.7	171.7	184.9	52.2	514.3	1.0829	19.0
3.	(46-0-0)	(20,70,70)+80[2]	6.54	37.4	63.7	158.6	177.6	55.0	492.3	1.0862	26.0
4.	(46-0-0)	(20,70,70)	1.85	20.1	74.0	197.1	167.1	44.1	502.4	1.0877	16.0
5.	(34-0-0)	(40,100,100)	2.53	30.4	72.6	173.5	164.7	44.5	485.7	1.0849	17.0
6.	(34-0-0)	(20,70,70)+80[2]	3.92	29.3	73.2	161.2	169.6	43.2	476.5	1.0851	12.0
7.	(34-0-0)	(20,70,70)	1.13	28.8	74.2	197.0	154.5	23.0	477.5	1.0875	21.0
8.	(34-0-0)	(40,40,40)	1.27	18.1	70.1	204.4	152.8	25.4	470.8	1.0861	20.0
9.	(34-0-0)	(40,40,40)+60[3]	1.34	22.5	74.4	183.1	157.5	39.5	477.0	1.0846	14.0
10.	(34-0-0)	(40,40,40)+80[2]	2.04	23.2	80.7	172.3	140.5	37.9	454.6	1.0823	15.0
Significance			*	*	*	**	**	**	**	*	*
BLSD (0.05)			3.25	19.6	16.5	25.6	38.2	20.2	57.3	0.004	11.5
Contrasts											
Lin Rate N (1, 5, 7, 8)			NS	*	++	NS	**	**	**	NS	*
Quad Rate N (1, 5, 7, 8)			NS	NS	NS	NS	**	**	**	NS	NS
Post-hilling (2, 5) vs (3, 6)			*	NS	NS	NS	NS	NS	NS	NS	NS
(2, 3, 4) vs (5, 6, 7)			NS	NS	*	NS	NS	*	NS	NS	NS
Treatment 3 vs 4			**	*	NS	**	NS	NS	NS	NS	*
Treatment 6 vs 7			++	NS	NS	**	NS	*	NS	NS	*
Treatment 9 vs 10			NS	NS	NS	NS	NS	NS	NS	NS	NS

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant; ++, *, ** = significant at 10%, 5% and 1%, respectively.

Table 3. Effect [illegible]rogen treatments on root and vine dry matter, tuber numb[illegible] dry matter; sampled June 20, [illegible] - Becker, MN.

	Treatment N source	N timing	Tubers	Tuber	Vine	Root	Total	Tuber	Vine	Root
				dry matter				N concentration		
			-#/plant-	g/plant				% N		
1.	Control	(0 N/A)	11.9	22.3	21.2	4.2	47.7	1.10	2.76	1.40
2.	(46-0-0)	(40,100,100)[1]	16.5	35.8	67.5	5.2	108.5	1.56	4.24	2.32
3.	(46-0-0)	(20,70,70)+80[2]	9.5	17.8	44.7	3.5	66.0	1.61	4.36	2.39
4.	(46-0-0)	(20,70,70)	9.5	20.3	46.3	3.5	70.1	1.73	4.49	2.47
5.	(34-0-0)	(40,100,100)	14.3	29.8	57.5	4.8	92.1	1.66	4.57	2.41
6.	(34-0-0)	(20,70,70)+80[2]	14.6	26.8	52.7	4.2	83.7	1.59	4.46	2.40
7.	(34-0-0)	(20,70,70)	13.4	28.5	64.0	4.3	96.8	1.64	4.45	2.28
8.	(34-0-0)	(40,40,40)	11.8	21.3	58.3	4.0	83.6	1.63	4.19	2.49
9.	(34-0-0)	(40,40,40)+60[3]	16.5	31.0	57.0	4.8	92.8	1.49	4.00	2.13
10.	(34-0-0)	(40,40,40)+80[2]	12.6	28.4	50.4	4.8	83.6	1.46	3.85	2.06
Significance			++	NS	**	++	**	**	**	**
BLSD (0.05)			6.9	--	14.4	1.5	29.6	0.27	0.30	0.26
Contrasts										
Lin Rate N (1, 5, 7, 8)			NS	NS	**	NS	**	**	**	**
Quad Rate N (1, 5, 7, 8)			NS	NS	*	NS	NS	*	**	**
Post-hilling (2, 5) vs (3, 6)			++	++	*	**	*	NS	NS	NS
(2, 3, 4) vs (5, 6, 7)			NS	NS	NS	NS	NS	NS	NS	NS
Treatment 3 vs 4			NS	NS	NS	NS	NS	NS	NS	NS
Treatment 6 vs 7			NS	NS	NS	NS	NS	NS	NS	NS
Treatment 9 vs 10			NS	NS	NS	NS	NS	NS	NS	NS

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant, ++, *, ** = significant at 10%, 5%, and 1%, respectively.

Table 4. Effect of nitrogen on N content, concentration, and dry matter production. Becker, MN

	Treatment N source	N timing	Vines	Tubers	Total	Vine	Tubers	Vines	Tubers	Total
			Nitrogen content			N concentration		Dry matter		
			lbs/A			% N		Tons/A		
1.	Control	(0 N/A)	3.6	66.0	69.6	0.75	0.88	0.24	3.78	4.02
2.	(46-0-0)	(40,100,100)[1]	15.1	143.9	159.1	1.05	1.30	0.73	5.64	6.37
3.	(46-0-0)	(20,70,70)+80[2]	30.6	154.1	184.7	1.43	1.40	1.07	5.54	6.61
4.	(46-0-0)	(20,70,70)	13.8	145.6	159.4	0.92	1.31	0.74	5.58	6.32
5.	(34-0-0)	(40,100,100)	21.3	147.9	169.1	1.38	1.42	0.78	5.21	5.99
6.	(34-0-0)	(20,70,70)+80[2]	27.1	146.1	173.2	1.67	1.38	0.80	5.31	6.11
7.	(34-0-0)	(20,70,70)	11.5	133.3	144.8	0.85	1.27	0.68	5.25	5.93
8.	(34-0-0)	(40,40,40)	11.1	119.5	130.6	0.72	1.12	0.76	5.34	6.10
9.	(34-0-0)	(40,40,40)+60[3]	13.4	141.0	154.4	1.11	1.37	0.62	5.15	5.76
10.	(34-0-0)	(40,40,40)+80[2]	15.5	132.9	148.4	1.26	1.35	0.61	4.99	5.60
Significance			**	**	**	**	**	*	**	**
BLSD (0.05)			12.2	24.1	31.1	0.19	0.18	0.48	0.93	1.10
Contrasts										
Lin Rate N (1, 5, 7, 8)			**	**	**	**	**	**	**	**
Quad Rate N (1, 5, 7, 8)			++	**	**	**	*	++	*	*
Post-hilling (2, 5) vs (3, 6)			*	NS	NS	**	NS	NS	NS	NS
(2, 3, 4) vs (5, 6, 7)			NS	NS	NS	**	NS	NS	NS	NS
Treatment 3 vs 4			**	NS	NS	**	NS	++	NS	NS
Treatment 6 vs 7			**	NS	++	**	NS	NS	NS	NS
Treatment 9 vs 10			NS	NS	NS	NS	NS	NS	NS	NS

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant, ++, *, ** = significant at 10%, 5%, and 1%, respectively.

Table 5. Effect of nitrogen treatments on nitrate-N concentration in potato petioles (dry weight basis) and nitrate concentration in petiole sap, as determined by various procedures. Becker, MN.

	Treatment: N source	N timing	June 4: dry weight Petiole-N	June 4: sap Horiba	June 4: sap Hach	June 4: sap Wescan	June 14: dry weight Petiole-N	June 14: sap Horiba	June 14: sap Hach	June 14: sap Wescan
			ppm NO_3-N							
1.	Control	(0 N/A)	6290	545	481	446	309	109	61	46
2.	(46-0-0)	(40,100,100)[1]	17969	1250	1259	1141	16522	1475	1225	1219
3.	(46-0-0)	(20,70,70)+80[2]	17052	1170	1165	1065	15435	1550	1219	1230
4.	(46-0-0)	(20,70,70)	16606	1125	1130	1019	13793	1313	1121	1082
5.	(34-0-0)	(40,100,100)	18170	1275	1233	1114	19061	1775	1465	1415
6.	(34-0-0)	(20,70,70)+80[2]	18103	1225	1224	1142	17445	1638	1358	1220
7.	(34-0-0)	(20,70,70)	17318	1200	1195	1136	16450	1525	1244	1216
8.	(34-0-0)	(40,40,40)	16945	1225	1198	1098	13572	1350	1051	1041
9.	(34-0-0)	(40,40,40)+60[3]	17480	1175	1156	1079	12990	1200	943	1033
10.	(34-0-0)	(40,40,40)+80[2]	16858	1215	1167	1105	11295	1158	979	948
Significance			**	**	**	**	**	**	**	**
BLSD (0.05)			1919	166	151	118	2024	147	137	117
Contrasts										
Lin Rate N (1, 5, 7, 8)			**	**	**	**	**	**	**	**
Quad Rate N (1, 5, 7, 8)			**	**	**	**	**	**	**	**
Post-hilling (2, 5) vs (3, 6)			NS	NS	NS	NS	++	NS	NS	++
(2, 3, 4) vs (5, 6, 7)			NS	NS	NS	NS	**	**	**	**
Treatment 3 vs 4			NS	NS	NS	NS	NS	**	NS	*
Treatment 6 vs 7			NS	NS	NS	NS	NS	NS	NS	NS
Treatment 9 vs 10			NS	NS	NS	NS	NS	NS	NS	NS

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant, ++, *, ** = significant at 10%, 5%, and 1%, respectively.

Table 5 cont. Effect of nitrogen treatments on nitrate-N concentration in potato petioles (dry weight basis) and nitrate concentration in petiole sap, as determined by various procedures. Becker, MN.

	Treatment: N source	N timing	June 28: dry weight Petiole-N	June 28: sap Horiba	June 28: sap Hach	June 28: sap Wescan	July 11: dry weight Petiole-N	July 11: sap Horiba	July 11: sap Hach	July 11: sap Wescan
			ppm NO_3-N							
1.	Control	(0 N/A)	546	96	56	43	47	122	44	20
2.	(46-0-0)	(40,100,100)[1]	20573	1275	1354	1384	13882	1150	1093	1031
3.	(46-0-0)	(20,70,70)+80[2]	22098	1525	1471	1536	21851	1613	1612	1500
4.	(46-0-0)	(20,70,70)	18047	1175	1225	1268	9112	733	657	628
5.	(34-0-0)	(40,100,100)	21173	1475	1388	1401	15931	1375	1286	1221
6.	(34-0-0)	(20,70,70)+80[2]	23342	1400	1386	1503	21891	1625	1590	1488
7.	(34-0-0)	(20,70,70)	17573	1363	1362	1363	10789	980	872	809
8.	(34-0-0)	(40,40,40)	9934	795	788	812	2483	355	280	248
9.	(34-0-0)	(40,40,40)+60[3]	17305	1035	1005	1105	10418	1010	903	846
10.	(34-0-0)	(40,40,40)+80[2]	19376	1275	1264	1266	19137	1325	1311	1234
Significance			**	**	**	**	**	**	**	**
BLSD (0.05)			2712	158	147	124	2843	152	164	145
Contrasts										
Lin Rate N (1, 5, 7, 8)			**	**	**	**	**	**	**	**
Quad Rate N (1, 5, 7, 8)			**	**	**	**	*	**	**	**
Post-hilling (2, 5) vs (3, 6)			++	NS	NS	*	**	**	**	**
(2, 3, 4) vs (5, 6, 7)			NS	++	NS	NS	NS	**	*	*
Treatment 3 vs 4			*	**	**	**	**	**	**	**
Treatment 6 vs 7			**	NS	NS	*	**	**	**	**
Treatment 9 vs 10			**	**	**	*	**	**	**	**

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 ounds N/A each, based on sap analysis. [3] ee post-hilling applications at 20 pounds N/A each, bas ap analysis. NS = Nonsignificant, ++, = significant at 10%, 5%, and 1%, respectively.

Table 5 cont. Effect of nitrogen treatments on nitrate-N concentration in potato petioles (dry weight basis) and nitrate concentration in petiole sap, as determined by various procedures. Becker, MN.

	Treatment: N source	N timing	July 25: dry weight Petiole-N	July 25: sap Horiba	July 25: sap Hach	July 25: sap Wescan	August 8: dry weight Petiole-N	August 8: sap Horiba	August 8: sap Hach	August 8: sap Wescan
			ppm NO_3-N							
1.	Control	(0 N/A)	32	61	26	4	39	270	33	10
2.	(46-0-0)	(40,100,100)[1]	3534	360	298	266	1340	418	190	159
3.	(46-0-0)	(20,70,70)+80[2]	9928	1028	907	826	2998	629	395	357
4.	(46-0-0)	(20,70,70)	1759	198	167	143	846	281	96	71
5.	(34-0-0)	(40,100,100)	6225	653	537	502	2101	486	258	227
6.	(34-0-0)	(20,70,70)+80[2]	11743	1060	893	839	4508	643	441	397
7.	(34-0-0)	(20,70,70)	2619	248	196	174	563	295	84	63
8.	(34-0-0)	(40,40,40)	402	62	35	17	52	253	46	26
9.	(34-0-0)	(40,40,40)+60[3]	6119	665	591	547	1753	425	238	201
10.	(34-0-0)	(40,40,40)+80[2]	7771	635	539	498	1884	441	280	244
Significance			**	**	**	**	**	**	**	**
BLSD (0.05)			2411	164	149	137	2029	101	93	86
Contrasts										
Lin Rate N (1, 5, 7, 8)			**	**	**	**	*	**	**	**
Quad Rate N (1, 5, 7, 8)			NS	*	*	*	NS	++	*	*
Post-hilling (2, 5) vs (3, 6)			**	**	**	**	**	**	**	**
(2, 3, 4) vs (5, 6, 7)			*	*	++	*	NS	NS	NS	NS
Treatment 3 vs 4			**	**	**	**	*	**	**	**
Treatment 6 vs 7			**	**	**	**	**	**	**	**
Treatment 9 vs 10			NS	NS	NS	NS	NS	NS	NS	NS

[1] = Planting, emergence and hilling respectively. [2] = Four post-hilling applications at 20 pounds N/A each, based on sap analysis. [3] = Three post-hilling applications at 20 pounds N/A each, based on sap analysis. NS = Nonsignificant, ++, *, ** = significant at 10%, 5%, and 1%, respectively.

Table 5 cont. Effect of nitrogen treatments on nitrate-N concentration in potato petioles (dry weight basis) and nitrate concentration in petiole sap, as determined by various procedures. Becker, MN.

	Treatment: N source	N timing	August 22: dry weight Petiole-N	August 22: sap Horiba	August 22: sap Hach	August 22: sap Wescan
			ppm NO_3-N			
1.	Control	(0 N/A)	168	148	60	21
2.	(46-0-0)	(40,100,100)[1]	1638	218	160	105
3.	(46-0-0)	(20,70,70)+80[2]	2685	353	310	249
4.	(46-0-0)	(20,70,70)	1023	170	106	63
5.	(34-0-0)	(40,100,100)	1486	266	241	171
6.	(34-0-0)	(20,70,70)+80[2]	2886	310	359	270
7.	(34-0-0)	(20,70,70)	562	191	115	67
8.	(34-0-0)	(40,40,40)	265	135	69	26
9.	(34-0-0)	(40,40,40)+60[3]	963	210	176	119
10.	(34-0-0)	(40,40,40)+80[2]	2543	278	277	194
Significance			*	**	**	**
BLSD (0.05)			2191	123	168	134
Contrasts						
Lin Rate N (1, 5, 7, 8)			NS	*	*	*
Quad Rate N (1, 5, 7, 8)			NS	NS	NS	NS
Post-hilling (2, 5) vs (3, 6)			++	*	*	**
(2, 3, 4) vs (5, 6, 7)			NS	NS	NS	NS
Treatment 3 vs 4			++	**	*	**
Treatment 6 vs 7			*	*	**	**
Treatment 9 vs 10			++	NS	NS	NS

[1] = Planting, emerge d hilling respectively. [2] = Four post-hilling applicatio 0 pounds N/A each, based on sap analys = Three post-hilling applications at 20 pounds N/A each d on sap analysis. NS = Nonsignificant, *, ** = significant at 10%, 5%, and 1%, respectively.

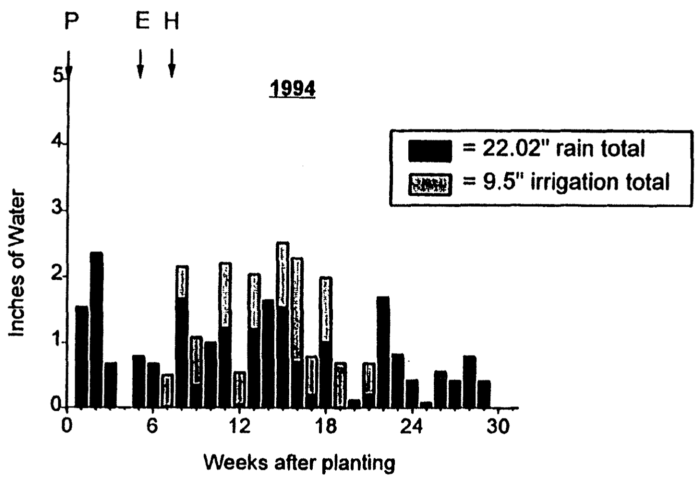

Figure 1. Rainfall and irrigation at Becker, MN during the 1994 growing season. P, H and E = planting, emergence and hilling, respectively.

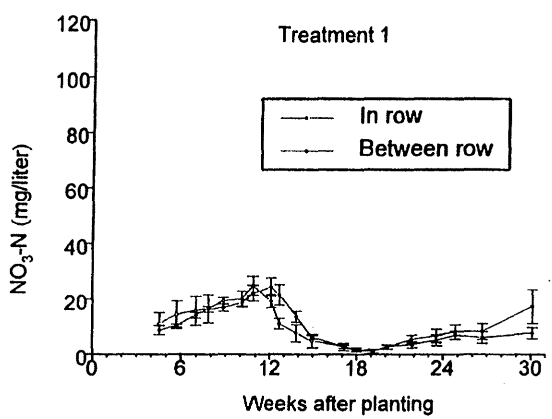

Figure 2. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: no nitrogen. Error bars represent SE of the mean.

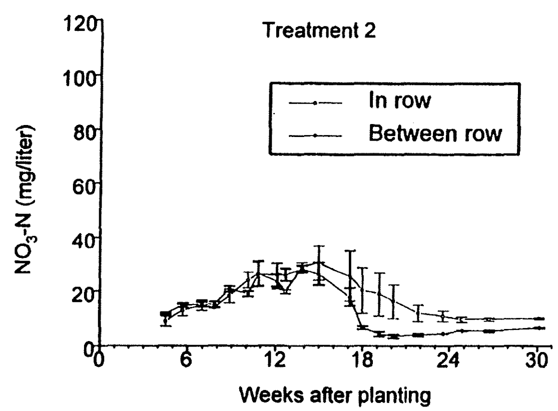

Figure 3. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: 40 lb N/A at planting, 100 lb at emergence and hilling (46-0-0). Error bars represent SE of the mean.

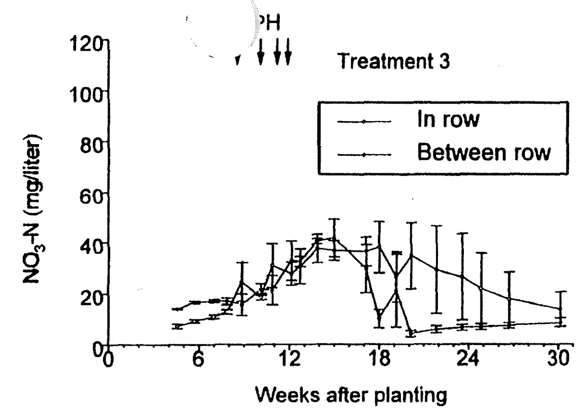

Figure 4. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: 20 lb N/A at planting, 70 lb at emergence and hilling, plus 4 post-hilling applications at 20 lb N/A each (46-0-0). Error bars represent SE of the mean. PH = post-hilling applications.

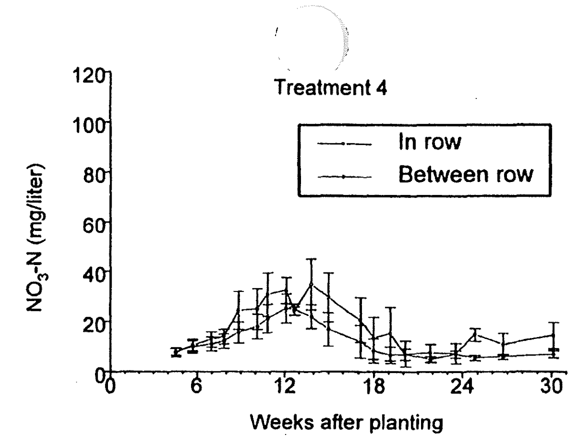

Figure 5. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: 20 lb N/A at planting and 70 lb at emergence and hilling (46-0-0). Error bars represent SE of the mean.

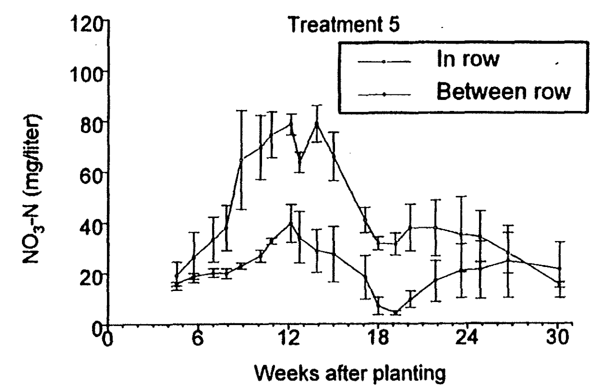

Figure 6. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: 40 lb N/A at planting, 100 lb at emergence and hilling (34-0-0). Error bars represent SE of the mean.

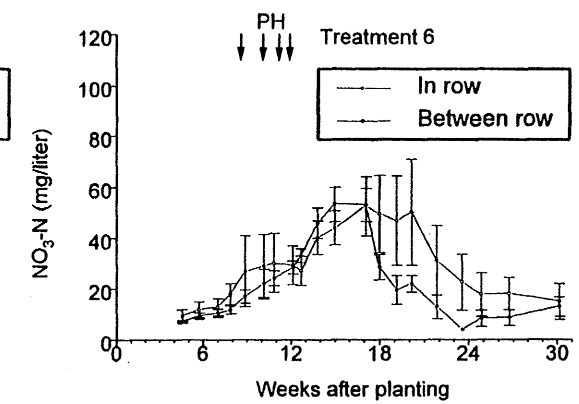

Figure 7. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: 20 lb N/A at planting, 70 lb at emergence and hilling, plus 4 post-hilling applications at 20 lb N/A each (34-0-0). Error bars represent SE of the mean. PH = post-hilling applications.

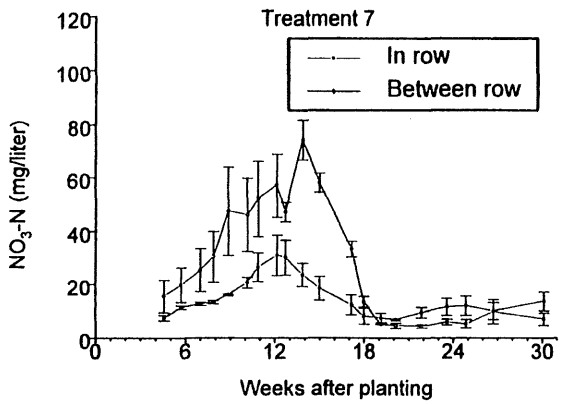

Figure 8. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: 20 lb N/A at planting and 70 lb at emergence and hilling (34-0-0). Error bars represent SE of the mean.

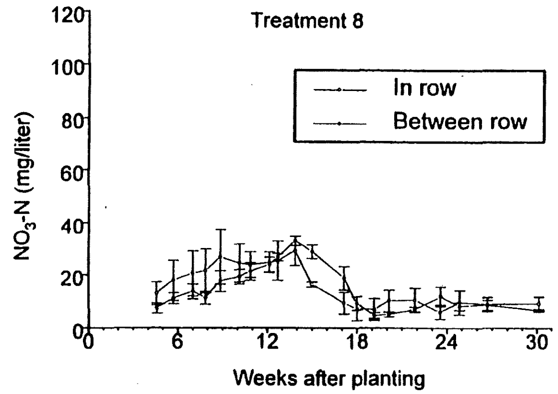

Figure 9. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: 40 lb N/A at planting, emergence and hilling (34-0-0). Error bars represent SE of the mean.

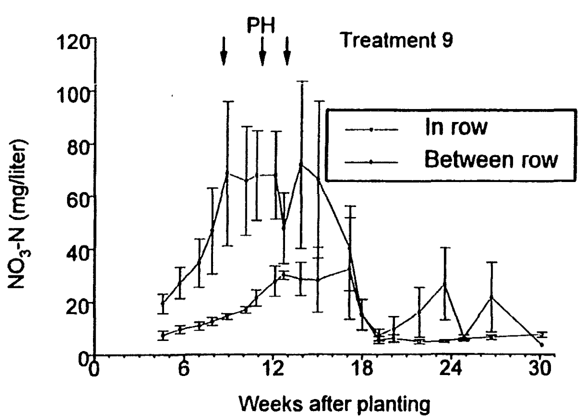

Figure 10. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: 40 lb N/A at planting, emergence and hilling, plus 3 post-hilling applications at 20 lb N/A each (34-0-0). Error bars represent SE of the mean. PH = post-hilling app[illegible]ns.

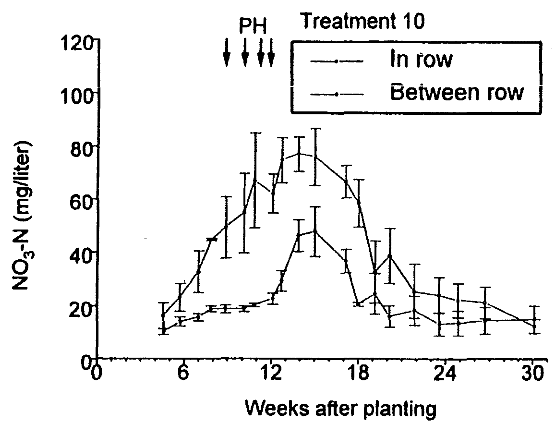

Figure 11. Nitrate - N concentration in soil water sampled in the row and between the row at the 4 ft. depth, over the 1994 growing season. Nitrogen application rate: 40 lb N/A at planting, emergence and hilling, plus 4 post-hilling applications at 20 lb N/A each (34-0-0). Error bars represent SE of the mean. PH = post-hilling applications

CALIBRATION OF THE PETIOLE NITRATE SAP TEST

The petiole nitrate sap test was calibrated for Russet Burbank potato using data from the 1991 to 1993 field seasons. The 1994 field season was not included because of an uncontrolled insect and disease outbreak which affected nitrogen response.

Two calibration curves are presented (figures 1 and 2). The curves in figure 1 were established by determining petiole sap nitrate-N levels through the season in the treatments that gave the highest yield in 1991 to 1993. A linear relationship was found to adequately describe the decrease in nitrate-N through the season for the highest yielding treatments. The sap nitrate-N levels through the season were also plotted for the treatments that gave about a 10% decrease in yield. A quadratic relationship described the decrease in sap nitrate-N levels through the season for the underfertilized plots. From these data, deficient, marginal and adequate to excess ranges have been defined (see figure 1).

An alternate approach was also taken to establish an "optimum range" for nitrate-N in petiole sap through the season (figure 2). For this approach, a ± 10-15% range on the line that delineates the marginal range from the adequate to excess range (figure 1) was given. The range that resulted is considered the "optimum range".

The optimum ranges determined above were used to schedule N fertigation for the experiments outlined in Objective C1. These figures have also been mailed to growers and consultants for use during the 1995 season.

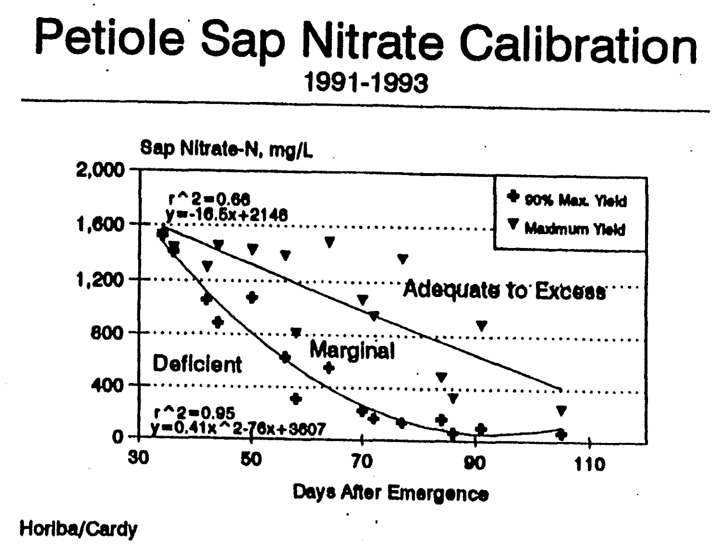

Figure 1. Seasonal deficiency, marginal, and sufficiency ranges for petiole sap nitrate-N.

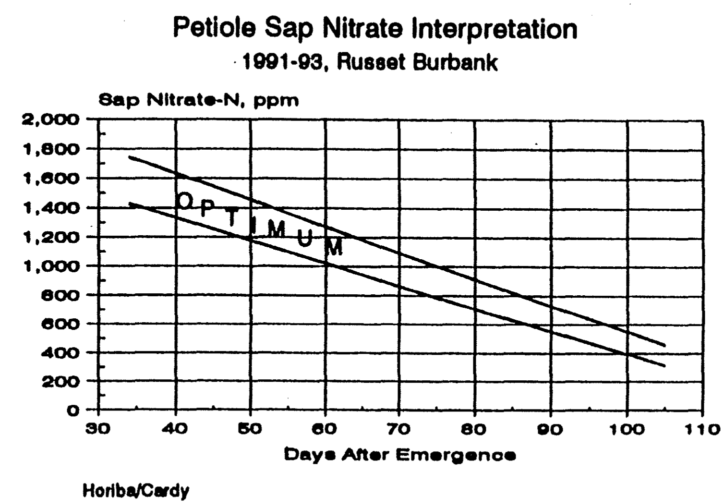

Figure 2. Seasonal petiole sap nitrate-N optimum ranges.

C. Title of Objective: Improve best management practices for irrigated potatoes and corn

C.1. Activity: Evaluate petiole sap-based N management on the basis of nitrate leaching, marketable yield, and costs and compare to conventional N management.

C.1.a. Context within the project: The petiole sap N criteria developed in Objective B will form the basis of a best management practice for irrigated potatoes. For early season sap tests, N applications could be made in the hill; however, because field operations are more difficult once the canopy closes, N applications based on the post-hilling sap tests will need to be applied either through the irrigation system or as a non-burning foliar spray. Intuitively, these post-hilling applications based on an N test should result in more efficient N use. However, N applied with irrigation is subject to preferential infiltration between the row ridges due to stem- and canopy-flow. If roots are not present between rows when irrigation occurs, or if water flux is greater than root uptake, a pathway for N loss is created. Water and N movement within and between rows must be measured to determine the impact of sap nitrate-based N applications on nitrate losses from the system. Data from this objective will be used for computer model validation in Objective E.

C.1.b. Methods: Sap based N management will be evaluated on the basis of nitrate leaching, marketable yield, and costs in a two-year experiment using the Russet Burbank potato cultivar. Less nitrate leaching without yield reduction relative to conventional N management will be the desired characteristics of new N management strategies based on petiole nitrate sap analysis. Detailed small plot experiments will be conducted at Staples and Becker Research stations in conjunction with objective B.

Nitrogen management demonstrations on growers fields will also be conducted over a two year period near Becker and Park Rapids, MN.

Treatments: Two treatments will be tested: 1) conventional grower N application with no post-hilling N (prehilling will be split into three applications- 45 kg N/ha at planting, 110 kg N/ha at emergence, and 110 kg N/ha at hilling), and 2) N applied conservatively up to hilling (45 kg N/ha at planting, 55 kg N/ha at emergence, and 55 kg N/ha at hilling), and then N applications based on sap tests starting one week after hilling. A randomized complete block design with four replications will be used. Yield and N uptake will be measured as described in Objective B.

For the grower field experiments, two center pivots of potatoes will be compared at each location. For each pivot, N on one half will be managed using conventional grower practices and on the other half, N will be managed using petiole sap test recommendations. Marketable yield from each pivot, N fertilizer inputs, and overall costs related to N management will be compared. Grower field days will be conducted each year during the growing season.

C.1.c. Materials: Suction cup samplers, pressure transducer equipped tensiometers, laboratory supplies, and field dataloggers will be needed to carry out this experiment.

C.1.d. Budget: $54,500, **Balance:** $0

C.1.e. Timeline	7/93	1/94	6/94	1/95	6/95
Establish field plots	xxx		xxxxx		
Collect petiole samples	xxx		xxxxx		
Measure soil water nitrate	x		xxxxx		
Measure soil water flux	xxxx		xxxxx		
Analyze data and costs		xx		xxxxx	

C.1.f. Status: Research Plots at Staples. Experimental plots were established at the Staples Irrigation Center during the 1993 and 1994 growing seasons. Two nitrogen fertilization schemes were compared - one employing the use of solid fertilizer up through the hilling stage (conventional) and the other using lower rates of solid fertilizer through hilling followed by N fertigation applications based on the sap test. Water distribution patterns at the soil surface were monitored by use of plastic cups. Canopy water retention and stemflow were calculated. Soil water samples were collected from suction cup samplers located in the furrow and in the row. Samples were tested for nitrate concentration. Water movement was calculated by monitoring the soil matric potential. From these values the N loss below the rooting zone was calculated for both the plant rows and furrows between rows. For comparison purposes, nitrate leaching was calculated using an N budget where unaccounted for N was included with leached N. The following N budget was used: Fertilizer N input + Mineral soil N in the spring + Mineralized N - Plant N - Residual soil N at harvest = N leached + N unaccounted for. This budget was used to determine if processes other than leaching (denitrification, volatilization, immobilization) need to be included/measured.

Measurement of throughfall patterns through the showed that the plant canopy initially shed water similar to an umbrella, and that the quantity of water held by the plant canopy and channeled down stems was insignificant. Early in the growing season, plant vines were upright resulting in more water being deposited in the furrows than the rows. Later in the season, when the vines slumped and leaf area was lower in the row than in the furrow, more water was deposited in the row than in the furrow. The implication of this finding is that fertigation applications made too early in the season may result in N losses from the furrow, especially if roots are not present in the furrow.

Measured water leaching over the growing season showed that more was lost from the furrow than the row. There was no significant difference between row position with respect to N loss, indicating that nitrate concentrations were higher in the row than in the furrow. A greater quantity of N was lost with the conventional treatment in 1993. There were no significant differences between the two treatments in 1994, although the trend was similar to that in 1993. These results indicate that the petiole sap test is a useful tool to schedule N fertigation applications and that fertigation does not increase overall leaching of nitrate during the growing season.

Comparison of nitrate leaching calculated by an N budget with measured nitrate leaching showed a large discrepancy between the two methods, with measured nitrate leaching much lower than calculated nitrate leaching. Assuming that measured nitrate leaching losses were reasonably accurate, these results indicate that processes not directly measured in this study such as immobilization, denitrification, and volatilization (unaccounted for N) need to be measured to develop a meaningful N budget.

<u>On-farm demonstrations</u>. Improved N management strategies were demonstrated in growers fields during the 1993 and 1994 growing seasons. In 1993, two potato pivots near Park Rapids (Hubbard County) and one potato pivot near Becker (Sherburne County) were monitored. In 1994, one potato pivot near Park Rapids and one near Becker were monitored. Russet Burbank was the potato cultivar used in all demonstrations. The original plan was to manage half of each field according to conventional grower procedures and the other half using improved N management strategies. The improved strategies included: reduced N at planting (< 40 lb N/A), reduced N at emergence (70-90 lb N/A), reduced N at hilling (70-90 lb N/A), post-hilling N applications would be based on the sap test. In the past, conventional grower procedures included 60 to 100 lb N/A at planting, and 80 to 100 lb N/A at emergence and hilling. Post-hilling applications were not usually based on any diagnostic criteria. Unfortunately, we were unable to get the growers to follow these conventional procedures in our demonstrations. Growers more or less mimicked the improved management practices on both sides of the field. There were some differences in N management between either side of the field, but not as different as we had hoped. The demonstrations were still useful because other growers in the areas were made aware that these improved practices did not detrimentally affect yield and quality.

Overall results of the five demonstrations showed that 30 lb N/A less can be applied using improved practices with no negative effects on yield or quality. This saving in N fertilizer (about $600/100 acres) would more than offset the cost of monitoring a 100 acre field for petiole nitrate.

Use of both the demonstrations and field experiments from objectives B and C has resulted in the development of Nitrogen Best Management Practices for irrigated potatoes. The suggested BMPs developed have been sent out to growers for discussion and once the final revision is made, the BMPs will be adopted for use by the Minnesota Department of Agriculture and other state agencies.

C.2. Activity: Various nitrogen sources (manure and fertilizer) will be compared as to their efficiency of plant recovery and leaching losses under irrigated corn production. Soil type and climate effects will be evaluated.

C.2.a. Context within the project: Dairy and poultry livestock operations are an important part of the economy in North-central Minnesota. Environmentally sound manure and fertilizer nitrogen utilization from these farming enterprises is imperative. Preliminary data have shown that performance of anhydrous ammonia to be inconsistent when compared to other sources of N (urea-ammonium nitrate solutions, dry urea, and animal manures) in plant recovery and leaching losses. It is the cheapest fertilizer source however. Due to the nitrification inhibition that occurs with anhydrous ammonia due to the high pH and free ammonia in the injection zone, in a leaching year there should be less leaching and more available to corn. Manure sources of N have shown to be an advantage in a leaching year. The efficacy of manure as a nitrogen source is more dependent on fall and spring weather conditions. This objective will evaluate these sources of N under various precipitation distribution on sandy irrigated soils.

Data from this objective will be used for computer model validation in Objective E.1.

C.2.b. Methods: Corn will be grown in rotation with potatoes. The experimental design will be a randomized complete block with five N sources: urea, anhydrous ammonia, urea-ammonium nitrate solution, and turkey manure, All nitrogen will be applied using current best management recommendations for timing and N rate.

Corn and potato response will be characterized by measuring grain yields and total N uptake. Nitrate leaching losses will be estimated by determining nitrate concentrations in soil water collected using suction samplers placed below the root zone and by calculating water flow using measured rainfall data, irrigation data, crop ET estimates and established soil hydraulic conductivities. using transducer equipped tensiometers and suction samplers. The calculated water flow data and direct measurement of soil water nitrate concentration will be used to estimate nitrate flux.

C.2.c. Materials: suction samplers and laboratory supplies.
C.2.d. Budget: $54,500

C.2.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Establish treatments	xxxx		xxxx		
Collect soil water data	xxxx		xxxx		xxxx
Collect plant data	xxxx		xxxx		xxxx
Analyze data		xxxx		xxxxxxxxx	

C.2.f. Status: Sandy glacial outwash soils in central Minnesota are being cropped more frequently with potatoes. The presence of shallow groundwater tables coupled with coarse textured soils makes this region an especially high risk area for water quality degradation. Maintenance of maximum potato yields may be leading to further contamination of groundwater quality by agricultural chemicals. Nitrate has been found to be the major pollutant associated with groundwater in areas of intensive agriculture.

Minnesota, the second largest turkey producer in the U.S. has a surplus of turkey manure with high N content. This turkey manure may be a useful source of N for potato production and may result in reduced leaching potential for groundwater degradation by nitrates. Granular urea in split applications is the N management typically used by potato farmers in Minnesota. Other N sources used in the area, either on corn or potato, are anhydrous ammonia (AA) and urea-ammonium-nitrate (UAN) solution. To test which N source produces highest yield with lowest impact to the environment, we conducted a field experiment at Staples, MN.

The specific objectives of this two year study were to determine the effect of four different N sources in a corn and potato rotation on crop yield and quality, plant N uptake, and N leaching losses below the root zone.

In 1993, rainfall was plentiful except for a 20 day period beginning in late July extending into early August. Six cm of irrigation was supplied at four discrete times. Measured values include water from rain and irrigation. Estimated values include a daily summation of water use taken from a table in the Checkbook Method of Wright and Bergsrud, 1980. It has been shown by Dylla et. al. (1980) that the water use tables of Wright and Bergsrud are comparable to estimates obtained by more precise methods. Therefore, knowing total applied water, plant use, and soil storage (six cm),the resultant parameter (leachate) can be estimated. Corn was supplied 66.1 cm, used 36.3cm, and leached 31.5 cm of water in 1993. The remaining water (1.7 cm) is accounted for in soil storage. Corn in 1994 was supplied with 38.9 cm, used 38.0 cm, and leached 6.2 cm in 1994. No water excess occurred after 24 June (175), 1994. Irrigation equipment malfunctions caused a late season deficit to reach 5.3 cm (88 % of the available water holding capacity (AWHC) in 1994, perhaps limiting yield of both corn and potato.

The potato water summary was very similar to the corn summary for individual years. Potato used three cm less water than corn in 1993 and 1 cm more water than corn in 1994. Because rainfall and irrigation were the same for corn and potato, the only other different variable is leachate. In 1993, 31.5 cm leached past the root zone and in 1994, 4.5 cm leached leading to the qualitative conclusion of calling 1993 a leaching year and 1994 a non-leaching year.

No effects of N source were observed in 1993. Grain yields were higher than the control. Stover yields were not different than the control in all treatments. Turkey manure and urea yielded the most grain in 1994. Stover harvested on turkey manure plots was the only treatment not different than control. Yields in 1994 were higher than 1993 except for the control. Turkey Manure or urea split applied are acceptable N sources for corn on irrigated sandy soil.

Plots with turkey manure, urea, and anhydrous ammonia gave highest marketable tuber yield in 1993. The urea-ammonium nitrate solution treatment (UAN) yielded significantly less marketable tubers than granular urea and AA, but was not significantly different than the turkey manure treatment. The urea treatment produced the most tubers but was not significantly different than total yields under turkey manure and AA fertilization. The urea treatment gave greatest vine yields while other N sources produced significantly less vines.

In 1994, there was no effect of N source in marketable tuber yield. The turkey manure, urea, and anhydrous ammonia treatments had highest total tuber yield. At harvest in 1994, vines in the turkey manure plots were still green, while vines in other treatments had died.

The difference between total and marketable tuber yields give an estimate of non-marketable tubers which corresponds to low quality. In 1993, the difference between total and marketable tubers is lowest (2.3 Mg ha^{-1}) in the AA treatment indicating higher production efficiency. Excluding the control, in 1994 turkey manure was the most efficient N source. Turkey manure is an acceptable N source for tuber yield and produces high quality tubers. Nitrogen sources other than 28% can be used at similar rates to achieve similar yield. Late season N release occurs with turkey manure evident from vine data in 1994.

Having established a method for estimating water excess (assuming all excess is lost to subsurface reservoirs), we can calculate the volume of water per hectare. Multiplying the excess volume by the concentration of nitrogen from suction cup samplers gives the values with units of kg ha^{-1}. In 1993, before suction cup installation, a large leaching event on 24 May. Thirteen cm of unsampled excess water leached through the profile. The assumption of a concentration of 10 mg N L^{-1} based on soil solution concentrations from a nearby field, yields an event with calculated loss of 13 kg N ha^{-1}. Otherwise, it appears that nitrate is leached more under potato than corn. It is curious to note that the total nitrogen leached under the potato control was higher than all other treatments under corn in 1993.

Again, in 1994 as in 1993, nitrogen concentrations under potato were higher than corn, probably due to differences in rooting depths. Several dates with predicted leaching events on potato and not corn indicate periods which potato water use is greater than that of corn. The point where the ratio of potato:corn water use is one, was on 8 August,1993 and on 19 July,1994. Prior to these dates potato use is higher and after these dates corn use is higher. Generally, by these dates both corn and potato are at the onset of maturity and senescence and plant water use begins to decrease.

Comparisons of N lost under split urea application and turkey manure treatments indicate that in a leaching year, 1993, the mineralization of turkey manure creates excess nitrogen capable of being leached later in the growing season if not taken up by plants. This may be the case on 20 August, 1993, 30 kg ha^{-1}(almost half the treatment total) was leached in one event.

Another factor determining leachability of N is timing of the fertilizer application. On 11 July, 1993, 15 days after side-dressing of urea, 17 kg ha^{-1} leached with 2 cm water excess. During the last leaching event of the growing season on 1 September, 1993, the control treatment lost more N than urea treatments but lost less than the turkey manure treatment. This implies that the same mechanisms for soil organic matter mineralization may also regulate turkey manure mineralization.

Cumulative N losses during the 1994 growing season indicates that less leaching occurred over 1993. No leaching events occurred after June. The largest events leached less than 2 cm carrying 2 to 17 kg N ha^{-1}. Turkey manure contributes more to groundwater degradation than urea and control treatments.

In conclusion, nitrogen sources other than urea-ammonium nitrate solutions produced equivalent yields in a corn/potato rotation. Yields with urea-ammonium nitrate on the same soil tended to be lower than with other N sources. During the first half of the growing season, potato evapotranspiration exceeded corn ET, therefore less leaching occurred under potato. Later in the growing season, decreased potato water use was responsible for higher nitrogen fluxes past the root zone. Mineralization of turkey manure can contribute to nitrate contamination of leached water later in the growing season.

SURFACE DISTRIBUTION PATTERNS OF PRECIPITATION AND IRRIGATION UNDER A POTATO CANOPY AND RESULTING POSITIONAL DIFFERENCES IN NITRATE LEACHING

A THESIS SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL OF THE UNIVERSITY OF MINNESOTA

BY

BRADLEY MURRAY CARLSON

In partial fulfillment of the requirements for the degree of Master of Science

July 1995

WATER DISTRIBUTION PATTERNS UNDER A POTATO CANOPY

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In partial fulfillment towards the degree of Master of Science

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Introduction

Interactions between plant vegetative matter, and precipitation and irrigation water have been studied for many years. Early investigations concentrated on trees; however, a few studied smaller vegetation. Horton (1919) noted that approximately 15% of precipitation was intercepted by clover, but acknowledged that detailed study of crop canopies was lacking at that time. Haynes (1940) measured canopy interception by alfalfa, clover, and soybeans and reported that up to 35% of precipitation could be held, with an additional 15% being channeled down the stems of these broadleaves at maturity. Clark (1940) reported that some plants would intercept 90% of rainfall, but did not consider stem-flow. Many of these early investigations were the result of the dust bowl years, and thus were mainly concerned with quantities of water held by canopies, and then lost to evaporation. It is interesting to note that the studies mentioned previously found that relatively large amounts of water could be held by plant canopies, while a recent study by Ben-Hur and Plaut (1989) found that the presence of a cotton canopy did not alter the quantity of total runoff as compared to bare soil indicating that in some instances, or conditions the canopy held a very insignificant amount of water.

Other early studies, such as those of Gwynne and Glover (1961), and Shure and Lewis (1973), concentrated on the importance of water stem flow for plant survival. These studies did not quantify this phenomenon, but rather documented it's existence, and addressed it's importance.

Saffignia et al. (1976) first documented the potential importance of water stem flow and uneven water distribution at the soil surface in potatoes. They found that up to 46% of incoming water could be channeled down stems. Below ground observations following dye applications confirmed their stemflow readings. If this effect holds true, it could have major implications on the management of N inputs to potatoes. This study only reported measurements on one "fairly erect" plant at one growth stage making the applicability of their study to field conditions over the growing season questionable. Jefferies and MacKerron (1985) concluded with similar studies in Scotland that up to 86% of rainfall could be concentrated to stemflow. Their measurements were also conducted on erect plants with fairly low Leaf Area Indexes (LAIs) (1.8) and used "low intensity" rainfall and irrigation.

Values for stem flow reported by Saffignia et al. and Jefferies and MacKerron are similar to values for maize/corn obtained by Parkin and Codling (1990), Quinn and Laflen (1983), and Haynes (1940). Plant and canopy architecture of grasses and potatoes are very different in terms of height, flexibility, and physical strength. Potato vines, unlike many grasses, collapse at some point during the season so that the canopy becomes tangled and few stems are in an upright position. With that in mind, the findings of the potato studies cited above may be only applicable to the growth of potatoes prior to vine "slumping."

The object of this study therefore was to document stem flow and surface distribution patters of water underneath potato canopies through the growing season. It was hoped that this information would be useful when examining potato management practices with respect to losses of inputs to groundwater.

Materials and Methods

Research was conducted in 1993 and 1994 at the Staples Irrigation Center in Staples, Minnesota. The cultivar Russet Burbank was used. Row spacing was 91 cm and plants were 25 cm apart in the row. Nitrogen fertilizer as urea (46-0-0) was applied in three split applications for a total of 269 kgN/ha. All necessary climatological data were collected from a National Weather Service (NWS) official reporting station located 300 m from the plots. Leaf area index of the plots was monitored weekly in 1993 and as needed in 1994 with a Licor LAI-2000 portable leaf area meter. Leaf Area Indexes were recorded for row, shoulder, and furrow positions.

Water distribution under the plant canopy (throughfall) was monitored with plastic collection cups of known area placed in plant rows, shoulders, and furrows. Volumes were recorded following each precipitation or irrigation event. Cups were moved periodically to avoid effects from foot traffic. Collection began when the plant canopy began to extend to the shoulder and furrow positions (3 July in 1993, and 24 June in 1994), and was discontinued when the plants began to senesce (24 August in 1993, and 19 August in 1994).

In 1993 attempts were made to measure stem flow directly. Collars constructed from pieces of plastic test tube, plumbers putty, and flexible plastic tubing were installed on 15 stems chosen at random beginning when LAIs were approximately 1.5. When LAIs reached approximately 4.3, collar design was changed to a larger lipped plastic plate which could be adjusted for variable stem angle. Water was collected in plastic reservoirs, and measured after each rainfall or irrigation. Stems were harvested when collars were removed, and total leaf area was measured with a CID CI-251 leaf area meter. Collars were moved to new plants each week to avoid affecting plant growth and prevent biased readings. Volume of water per unit leaf area was calculated from the preceding week, and values translated to a field wide basis by multiplying by LAI. Readings were discontinued with the onset of senescence.

Due to extreme variability and perceived lack of success of stem flow collars, stem flow was also determined by use of a water budget. The equation used was: $\mathbf{F = PI - T - S}$, where F is the calculated stem flow, PI is precipitation plus irrigation, T is the throughfall water to the soil, and S equals canopy storage. Data gathered from the NWS weather station was used. The quantity of irrigation water was determined by using known settings on calibrated equipment. Throughfall was measured by collection as described above.

Canopy storage was determined by cutting off random plants, weighing them, and wetting them thoroughly. The plants were then agitated lightly to ensure no excess storage, and re-weighed. Total water storage was calculated by subtraction. Leaves were then removed and total leaf areas measured for calculation of storage per unit leaf area.

Results

The LAI graph for 1993 is relatively scattered, while the one for 1994 stays fairly smooth and consistent (figures 1 and 2). It should be noted that as the plants stretch out into the furrow the three positions equilibrate with respect to LAI, with peak LAI occurring soon after canopy closure. As the plants continue to grow after canopy closure they loose the ability to support their own weight, and slump together. This phenomenon is recognizable by the increase of LAI in the shoulder and furrow positions, and loss in the row. The timing of this slumping is only semi-predictable, and seems to be most dependent on climatic conditions. Heavy rainfall and high winds accelerated this process in 1993 (3 July) as can be noted from the LAI graph (figure 1). In 1994 there were no such events and the plants eventually collapsed under their own weight later in the season (24 July, figure 2). Examination of LAI graphs then reveal the presence of two stages of the full canopy. The first is characterized by equal or nearly equal LAIs for all row positions. The second stage begins when the vines slump, and can be defined as the point at which the LAI graph reveals significantly less leaf area in the row than in the shoulder positions.

When the growing season is split into the two previously mentioned stages different patterns of throughfall are evident for each. By plotting pooled data from 1993 and 1994 and then fitting a regression line fixed at the origin the preference of one position over another can be determined. Water throughfall tends to be concentrated in the shoulder and furrow positions during the early parts of the growing season (figure 3). Analysis of data collected during the second portion of the season (figure 4) reveals that more water enters into the row than the shoulder and furrow. Collection of throughfall was discontinued in both years before the plants were completely dead. This decision to end collection was based on perceived poor canopy health that resulted in the equilibrium of throughfall patterns with respect to position.

Observed problems in 1993 with stemflow collars included: plugging of drainage tubes, disconnection of tubes caused by wind-induced plant movement, plant damage during installation and monitoring, and leakage from collars. These problems resulted in inconsistent data. Additionally there seemed to be a bias with installation favoring erect plants, while most stems during the later part of the growing season were slumped. Despite the problems many events were measured. These measurements were highly variable undoubtedly some were influenced by some of the afore mentioned problems. Since it was not possible to determine which readings were correct and which were flawed, the integrity of the direct measurements of stemflow were in doubt, and are therefore not reported.

Because throughfall totals for the season were very similar to the measured precipitation for both years (data not shown) it was decided to analyze the water budget for each rainfall or irrigation event and sum them for the season. Determination of retention by the canopy revealed a rate of .011 g H_2O / cm^3 leaf area which when regressed produces an r^2 of .93 (figure 5). Calculated yearly totals for canopy water retention showed that very little water is held and later evaporated from the canopy in relation to the seasonal precipitation totals (figure 6). Likewise the calculated stemflow was very small compared to the water that fell through the canopy to the soil surface.

Discussion

Throughfall is greater in the shoulder and furrow positions early in the season. Since there is little or minimal cover over the shoulders and furrows at that time there seems to be an umbrella effect from the plant canopy. That is, rather than channeling rainfall and irrigation, the canopy sheds the water outward. As mentioned earlier, LAI in the row is greater than or equal to that in the shoulder and furrow until some point after full canopy when the plants slump. It is at this point on there seems to be some favoring of the row position in terms of the quantity of water introduced to the soil surface. One should note the reduction in the LAI in the row area also at this time and the accompanying increase in throughfall quantities. Using the umbrella theory, It seems likely that the leaves in the furrow and shoulder, which are now in abundance, are shedding water towards the row.

Examination of the water budgets shows that the shoulder areas are the beneficiaries of slightly more water than the other two positions on a seasonal basis. Despite a slight overestimation of throughfall (data not shown), it obviously is the dominant process that affects water distribution at the soil surface. Calculation of canopy retention shows that it is quantitatively unimportant in the water budget. This concurs with Ben-Hur and Plaut. Surprisingly stemflow is also very small. On some individual dates 20% of total rainfall was calculated to be channeled down plant stems (data not shown), however the stemflow total is very small on a yearly basis. This is contrary to the findings of Saffignia et al. and Jefferies and MacKerron, but their experiments were conducted on erect plants, whereas this study focused on actual field conditions where plants did not remain upright for the entire growing season. However, because their studies indicated that stemflow can be significant, this experiment should not be interpreted that it does not exist. During the slumped period individual plants come in contact with the soil surface at many places in the shoulder and furrow areas. If there is stemflow, it is at these sites, not the center of the row, that water will be deposited. Considering this, it becomes questionable whether stemflow is either predictable or important. Some observations of Saffignia et al. also indicate that when plants are lying on the soil surface the effect of stemflow to the center of the row is minimized or eliminated.

Conclusions

Canopies do affect how and where incident precipitation and irrigation water reach the soil surface. They function as an umbrella rather than a funnel, and disperse water rather than concentrating it. There is less water distributed to the row position early in the growing season, but distribution changes to favor the row as LAI decreases in that position. Overall slightly more water was deposited to the shoulder area than to rows or furrows in 1993 and 1994. Direct measurement of stemflow on potatoes is difficult with the procedure employed by this study. Water calculated to be retained by the plant canopy or channeled as stemflow is very small, and probably of little importance with respect to overall management considerations.

References

Ben-Hur, M., and Z. Plaut. 1989. Cotton Canopy and drying Effects on Runoff During Irrigation With Moving Sprinkler Systems. Agronomy Journal 81:752-757.

Clark, O.R. 1940. Interception of Rainfall of Prairie Grasses, Weeds, and Certain Crop Plants. Ecological Monographs 10:245-277.

Gwynne, M.D. and J. Glover. 1961. Light Rainfall and Plant Survival Measurement of Stem Flow Run-off. Nature 191:1321-1322.

Haynes, J.L. 1940. Ground Rainfall Under Vegetative Canopy of Crops. Journal of the American Society of Agronomy 32:176-184.

Horton, R.E. 1919. Rainfall Interception. Monthly Weather Review 47:603-623.

Jefferies, R.A., and D.K.L. MacKerron. 1985. Stemflow in Potato Crops. Journal of Agricultural Science 105:205-207.

Parkin, T.B., and E.E. Codling. 1990. Rainfall Distribution Under a Corn Canopy: Implications for Managing Agrochemicals. Agronomy Journal 82:1166-1168.

Quinn, N.W., and J.M. Laflen. 1983. Characteristics of Raindrop Throughfall Under Corn Canopy. Transactions of the American Society of Agricultural Engineers 26:1445-1450.

Saffignia, P.G., C.B. Tanner, and D.R. Keeney. 1976. Non-Uniform Infiltration Under Potato Canopies Caused by Interception, Stemflow, and Hilling. Agronomy Journal 68:337-342.

Shure, D.J., and A.J. Lewis. 1973. Dew Formation and Stem Flow on Common Ragweed. Ecology 54:1152-1155.

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Figure 2. Progressive LAI values by row position for 1994.

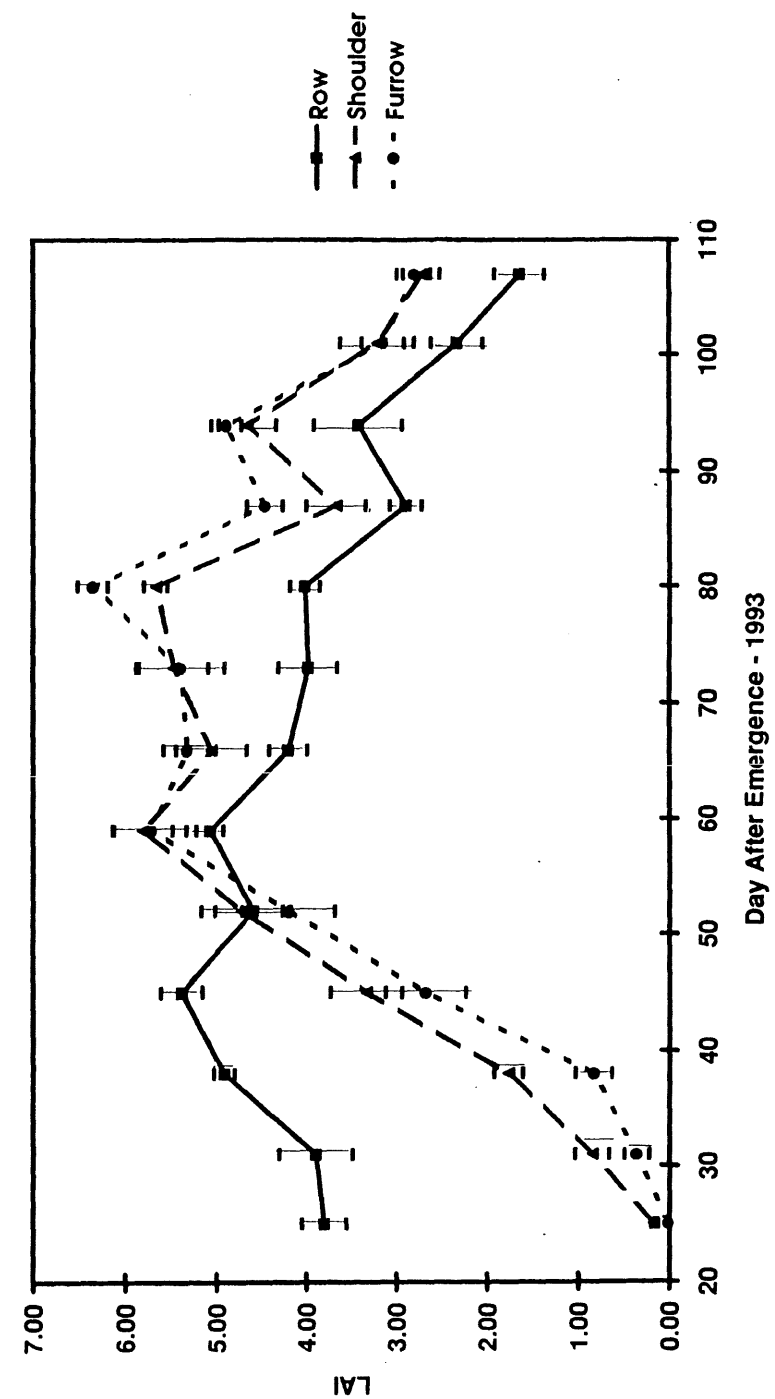
Figure 3. Throughfall distribution by row position for the first part of the growing season. Lines represent the regression of the points of each row position. Pooled data for 1993 and 1994 is used. Additional information is recorded in Table 1.

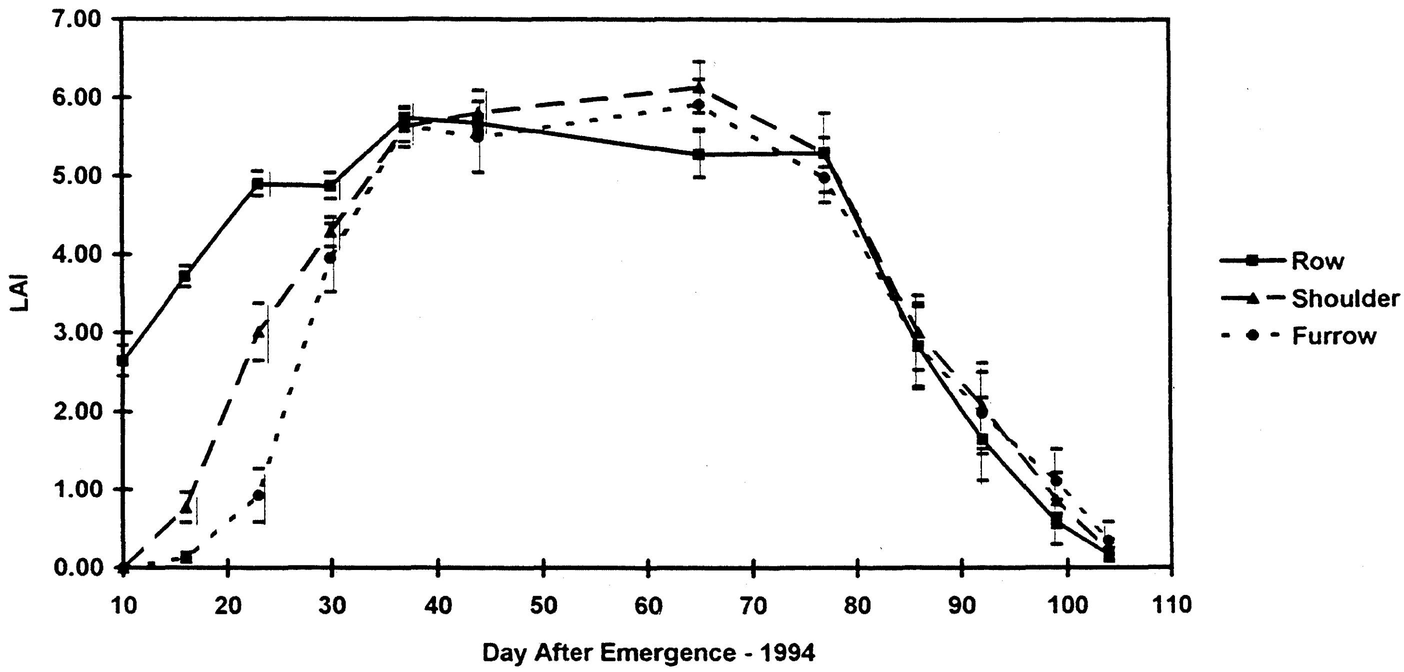
Figure 4. Throughfall distribution by row position for the slumped part of the growing season. Lines represent the regression of points of each row position Pooled data for 1993 and 1994 is used. Additional information is recorded in Table 1.

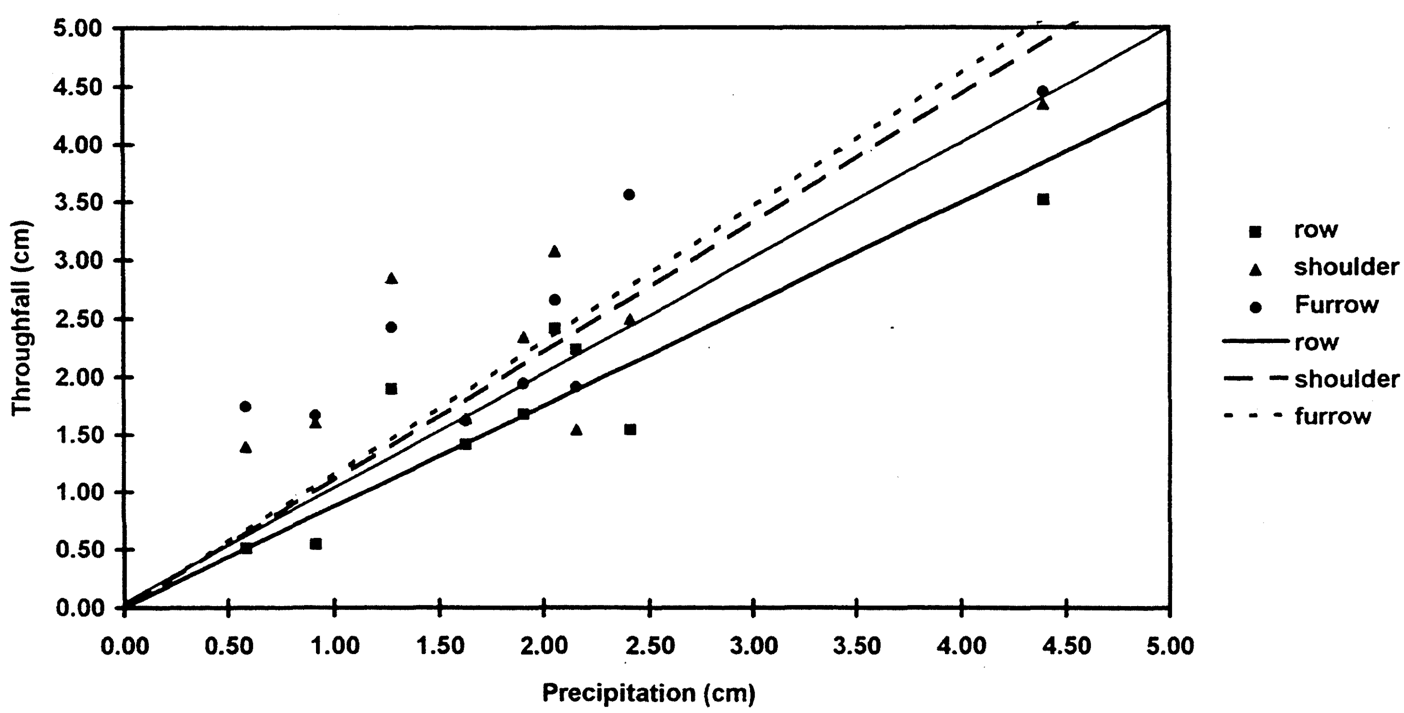
Figure 5. Measured canopy water retention expressed as quantity of water held per unit leaf area.

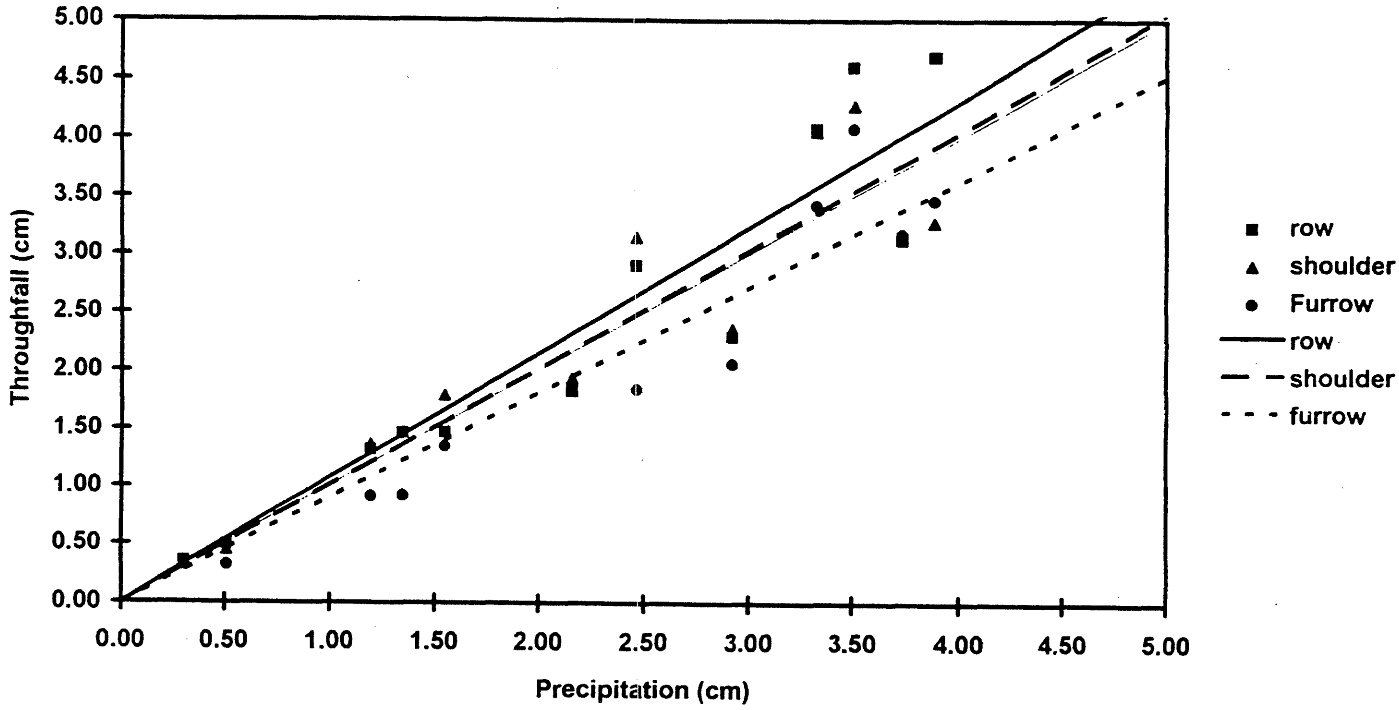
Figure 6. Yearly Sums of measured and calculated positional water distribution phenomenon.

Table 1. Summary of data from the regression of throughfall data.

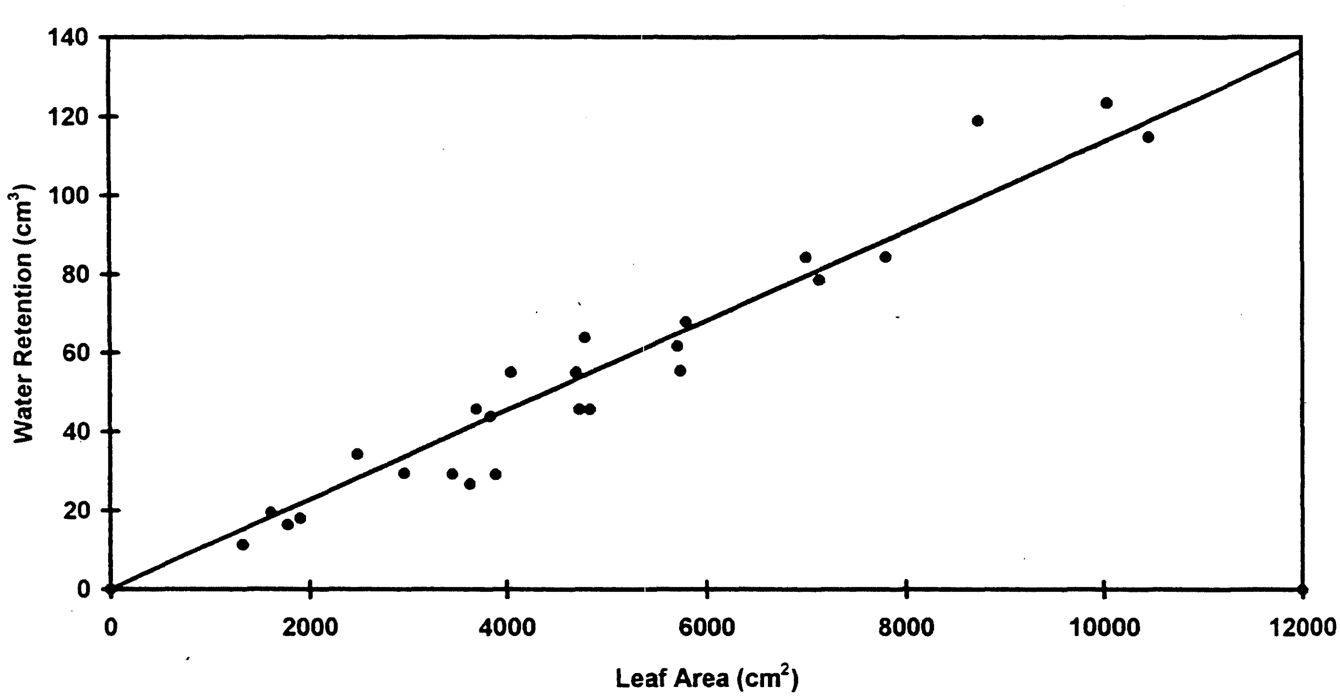



7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
LAI
10
20
30
40
50
60
70
80
90
100
110
Day After Emergence - 1994
Row
Shoulder
Furrow


5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Throughfall (cm)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
Precipitation (cm)
row
shoulder
Furrow
row
shoulder
furrow



Throughfall (cm)
Precipitation (cm)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
row
shoulder
Furrow
row
shoulder
furrow



Water Retention (cm³)
Leaf Area (cm²)
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20
40
60
80
100
120
140
2000
4000
6000
8000
10000
12000

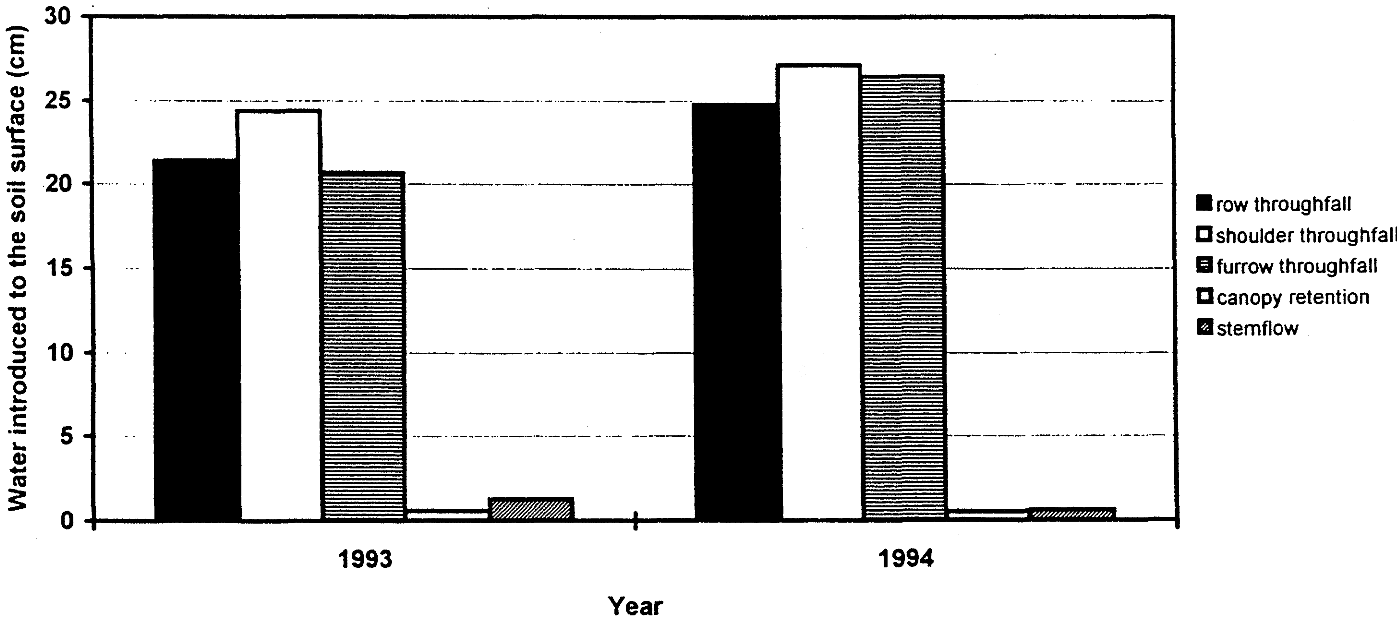

Table 1

Table 1.

	-----Upright Canopy-----			-----Slumped Canopy-----		
	Slope	SE	r^2	Slope	SE	r^2
Row	0.87	0.07	0.77	1.08	0.06	0.88
Shoulder	1.11	0.12	0.36	1.01	0.06	0.85
Furrow	1.15	0.11	0.48	0.91	0.04	0.91

COMPARISON OF TWO N MANAGEMENT SYSTEMS WITH RESPECT TO NITRATE LEACHING IN POTATOES

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Introduction

Potato culture on sandy soil requires high nitrogen (N) inputs for optimum production. Nitrogen rates as high as 360 kg/ha have been shown to be agronimically acceptable (Painter and Augustin, 1976). There is a need for developing a better N fertilization strategy since standard management practices of high rates applied early in the season have lead to unacceptable levels of nitrate in groundwater (Milburn, et al., 1990).

Reducing total application rates of N by as much as 25% has been shown to have no significant effect on yield, but increased variability, thereby increasing the risk of poor yields (Neeteson, 1989). Saffignia et al. (1977) suggested that N applied in many split applications would reduce N present in the soil for any given leaching event, resulting in less N loss per unit of N applied. Roberts et al. (1982), and Lauer (1985) confirmed the benefits of many split N applications. Ojala et al. (1990) proposed that properly timed splits of N may also benefit tuber production by facilitating N availability later in the growing season when the tubers are bulking. The benefits of smaller, multiple applications of N to reduce leaching losses seems logical, as Sexton (1993) showed that most nitrate leaching under potatoes in Central Minnesota was isolated to a few specific days. With multiple applications of smaller amounts of fertilizer, the quantity of N available on any given day to be leached from the soil is less than if larger amounts were applied. This management scheme also insures that more N will be applied later to replenish what is lost.

Saffignia et al. (1977) suggested that as many as ten split applications of N applied with irrigation water (fertigation) would be a better management practice for potatoes than a few applications early in the season. The application of ten splits seems impractical since many producers may not be willing to adopt this level of intensive management. In addition, application of N early in the season as fertigation could increase leaching potential due to the usual abundance of soil water at this time along with a poorly developed root system.

Another efficient approach might be to determine plant needs, and fertilize accordingly, rather than utilize an application schedule to attain some standard rate. If current physical assets could be used in a new system, producers would be more likely to modify N management practices. Many operators currently use IPM principles, logically this approach could be used to efficiently determine plant fertility needs. For this reason a system that involves routine testing of petiole sap nitrate levels by growers or crop consultants would be ideal (reference, 1999).

Since potential excess soil water may rule out the application of N by fertigation early in the growing season, the first splits could be applied as solid fertilizer by using traditional methods. Rates would be predetermined to provide adequate fertility levels during the first stages of growth. These applications could be scheduled to coincide with mechanical operations, such as planting, cultivation, or hilling. After hilling, the plant canopy is too large to withstand implement traffic. It is at this point that monitoring petiole sap nitrate levels would begin. From then on, N could be applied as needed in the form of fertigation.

Besides reducing total N applied, a management system utilizing fertigation may alter nitrate leaching by changing the spatial pattern of N applied. Saffignia et al. (1976) documented that a significant portion of precipitation and irrigation water could be channeled down stems, creating an uneven pattern of water distribution at the soil surface. If this affect is significant, water from fertigation could be placed directly in contact with roots, greatly increasing N efficiency. Carlson (1995), on the other hand, found that stemflow was not an important process for introducing water to the soil surface, rather that the vast majority of incident water interacted with the plant canopy and then fell to the soil surface. His observations indicate that the plant canopy tends to "shed" water much like an umbrella, rather than concentrate it. He noted changes in the surface distribution pattern over the growing season, where the row receives less water early in the season, and greater amounts later on. This change occurs at a point in the growing season when the canopy went from being mostly erect to being "slumped," or not capable of supporting it's own weight. This point can be identified by a reduction in the leaf area index of the row. These findings indicate that fertigation could lead to inefficient use of N early in the growing season by placing it further away from the plants, but lead to a more efficient use of N later in the season after incident water is redirected.

The objective of this research was to evaluate nitrate movement below the rooting zone as potentially affected by uneven distribution patterns of water at the soil surface. This study compared a N management system utilizing fertigation scheduled by petiole sap nitrate levels, to conventional N management which used only solid fertilizer.

Materials and Methods

The experiment was conducted at the Staples Irrigation Center in Staples, Minnesota. Soils present were Verndale sandy loam and Nymore sandy loam in 1993, and Verndale in 1994 (typical soils for potato production in this area). The Verndale soil is differentiated from the Nymore by a slight increase in clay content (leading to a defined argillic horizon) at approximately 25 cm depth. Russet Burbank cultivar potatoes were planted 25 cm apart in rows 91 cm apart. A two tower center pivot irrigator with drop nozzles was used to apply irrigation to the plots. Irrigation was scheduled using the checkbook method recommended by the Minnesota Extension Service (Wright and Bergsrud, 1994).

Plots measuring 5.49 m by 9.14 m were established using a factorial treatment design and replicated four times. All plots were in an arc which originated from the center of the irrigator and located under the last section of the irrigator. It was determined that this part of the irrigator would provide more even distribution of water. In order to apply fertigation to only half of the plots the irrigator was modified to allow the water to be shut off at either the front or back half of this last section.

Solid fertilizer rates were determined using best management practice recommendations as a guideline (Rosen, 1992). The total amount of N applied with the fertigated treatment was similar to the amount of N applied with the conventional treatment. The fertigated treatment was designed to apply less solid N early in the season followed by fertigation treatments based on a petiole sap test (Rosen, 1993). In addition to the fertilized plots, control plots receiving no N were established to determine the amount of N supplied by mineralization.

Urea (46-0-0) was used as the source of solid N fertilizer. Conventionally fertilized plots received 44.8 kg N/ha at planting, 112 kg N/ha at emergence, and 112 kg N/ha at hilling. Fertigated plots had 22.4 kg N/ha applied at planting, 78.4 kg N/ha at emergence, and 78.4 kg N/ha at hilling. The first treatment of solid fertilizer was banded into the planting furrow 5 - 6 cm on each side of the seed piece on 27 April in 1993, and 3 May in 1994. The second application of solid fertilizer was applied as surface bands approximately 10 cm from each side of the row at emergence (24 May in 1993, and 31 May in 1994). Bands were worked into the soil with a tractor mounted cultivator. The last application of solid N occurred at the time of hilling (17 June in 1993, and 13 June in 1994). This split was surface applied in the same manor as before, and was incorporated immediately after application during the hilling process.

Monitoring of petiole sap nitrate levels began one week after the final application of solid fertilizer. When petiole sap nitrate levels dropped below predetermined thresholds (Rosen and Errebbi, 1993), N was applied as fertigation at the rate of 22.4 kg N/ha. Fertigation treatments were usually applied with 0.5 cm of water unless irrigation scheduling dictated larger amounts. Plots not receiving fertigation had compensating amounts of water applied so that the same amount of water was applied to all plots. There were three fertigation treatments applied in 1993 (2 July, 15 July, and 30 July), and four in 1994 (24 June, 1 July, 13 July, and 30 July). Total N applied to conventional treatments was 269 kg/ha both years. Fertigated treatments received 246 kg N/ha in 1993, and 269 kg N/ha in 1994.

Water flux in both rows and furrows was calculated by using Darcy's equation. Unsaturated hydraulic conductivity was determined by using an equation derived by Campbell (1985). Saturated conductivity, and air entry potentials for Campbell's equation were taken from Sexton (1993), who used similar soils from adjacent plots. Slopes for water release curves were measured using tempe cells. Hydraulic gradients were determined by tensiometry in 1993. Matric potentials were measured in the row, and in the furrow by using tensiometers which were installed at 30 and 60 cm in 1993. From these measurements there was determined to be approximately unit hydraulic gradient below 30 cm throughout the growing season. For this reason there was assumed to be unit hydraulic gradient during both years. Due to field variability of soil physical properties (Biggar and Neilsen 1976) tensiometers were installed at 60 cm only (with unit gradient assumed) in 1994 which allowed for two replicate measurements per plot. Tensions were read approximately daily from planting until harvest.

Water samples were collected from ceramic cup vacuum samplers paired with each tensiometer in the row and furrow, at 60 cm depth. Samples were taken immediately following rainfall or irrigation, or once every seven days, whichever period was shorter. Nitrate concentrations were determined using a Wescan auto-analyzer (Carlson et al., 1990). Total N loss below 60 cm depth was calculated by using the average concentration method (Wagenet, 1986).

Leaf Area Index (LAI) was monitored using a Licor LAI-2000 so that canopy growth could be tracked, and the date of canopy slumping could be determined. Readings were taken weekly in 1993, and as needed in 1994 (so as to cause less canopy disturbance) for the row and furrow positions.

Plots were harvested on 16 September in 1993, and 21 September in 1994. The center two rows were harvested, sorted for grade, and weighed to determine yield.

For comparison purposes yearly N budgets were determined using the formula: **I + A + M - U - L - R = D**. Where I is the initial soil extractable inorganic N content; the factor A is the amount of N applied as fertilizer; M is the amount of N mineralized in the soil; U is the uptake by plants and tubers; L is the measured leaching loss; R is the residual N in the soil post-harvest; D is the discrepancy which can not be accounted for. Initial concentrations of inorganic N were measured by coring and extraction with 2N KCl (Carlson et al., 1990). Potato vine samples were taken just prior to harvest. Tuber subsamples were also taken. Vine and tuber samples were dried at 60° C to determine moisture content, then ground to pass through a 30 mesh screen. Total N concentration in tuber and vine samples was determined using the Kjeldahl / salicylic acid extraction method (AOAC, 1970) and Carlson (1978) method of analysis. Nitrogen content on a per hectare basis was then determined by multiplying N concentration in the tubers and vines times the yield in dry matter. Leaching loss was determined as mentioned above. The M values were determined by measuring the N uptake in the control plots. Soil samples were taken within a few days after harvest to determine residual inorganic N.

Results

Cumulative values for drainage were calculated for 1993 and 1994 (Figure 1). More water drained from under the furrow position than the row ($p<0.10$) for both years. There were no significant differences in water drainage between fertilizer treatments.

When soil water nitrate concentrations are considered, and total N loss is calculated, very different trends appear (Figure 2). Row position is not significant either year with respect to N loss below the rooting zone. More total N was leached from the nonfertigated plots than from the fertigated plots in 1993 ($p<0.10$). There were no significant differences between fertilizer treatments in 1994, although, total N leaching was 65% greater from the conventional plots.

Analysis of the LAIs confirm that there were four distinct periods of the growing season: early growth, full erect canopy, full slumped canopy, and senescence (Figure 3). Although not reported, data for both years showed similar patterns, with vine slump occurring earlier in 1993 than 1994.

For the purpose of evaluating the fertigation treatment, N loss totals for the second and third periods were summed (Figure 4) (these are the periods when fertigation was applied). There were few position / treatment / timing differences notable in 1993. The differences that do appear seem to be small and random. The 1994 data does show some definite trends. Most notable is that N loss below 60 cm in the furrow is similar for both treatments for both periods investigated. There are large differences in the loss from the row for both periods, with the conventionally managed plots loosing much more than the fertigated.

For yields, conventional plots averaged 46.3 Mg ha^{-1} in 1993, while fertigated yielded 45.7 Mg ha^{-1}. In 1994 the Conventional produced 50.6 Mg ha^{-1}, and the fertigated averaged 56.0 Mg ha^{-1}.

Calculation of N budgets produces very large D values (Table 1). Some of these values were up to 75% of the total N applied.

Discussion & Conclusions

Some factors which may cause different water drainage by row position are: plant root extraction, canopy redistribution of water at the surface, and hill geometry leading to runoff. Previous work by Carlson (1995) and Reece and Carlson (1994) rule out uneven surface distribution of water and surface runoff as potential sources of water accumulation to the row early in the season. Roots were not observed in any great quantity in the furrows, and the majority of water taken up by the plants was therefore assumed to be from the row area. This could have easily depressed the amount of water that passed below the root zone in the row as compared to the furrow. The circumstances therefore suggest that root uptake is the most significant factor leading to greater water loss from under the furrow.

In 1993 fertilizer treatment was significant to $p<.10$ in favor of the fertigated treatment reducing N loss compared to the conventional treatment. These differences were not significant in 1994, but variability was large and more replication may have allowed for a better comparison. It should be noted that the fertigated plots received over 20 kg/ha less N in 1993 than in 1994, so a difference is to be expected. Since yields did not suffer from the reduction of applied N it can be assumed that the sap testing method was successful in reducing inputs. Since there was significantly more water loss in the furrow than the row, and N concentrations were much higher in the row than the furrow, it seems that these two factors may have canceled out each other with respect to positional differences in N loss. By summing N loss positionally for the two canopy conditions of specific interest (erect and slumped) it is seen that some positions will lose more N at various times (figure 4). These differences can be large, but do not reveal a predictable pattern. In many cases neither of the positions dominates flow for an entire season, leading to no cumulative dominance of either position. These data show that monitoring only soil water nitrate concentration values does not allow for accurate comparison of positional differences in N leaching. Additionally, looking at only one position does not allow for accurate comparison of fertilizer treatments, which have possible year to year variability in climatic and pathogenic conditions.

The striking differences in N losses between 1993 and 1994 are caused by both the higher soil water nitrate concentrations and the greater water movement in 1994. Of these, water movement was perhaps the most important, for even if the nitrate concentrations had been higher in 1993 there was very little water movement to take it out of the system.

Since there is more leaf area in the row early in the season the umbrella phenomenon described by Carlson (1995) could possibly lead to greater leaching from fertigated plots since

N would be distributed more heavily in the furrow, placing it further away from plants. Fertigation applied after the plants have slumped will concentrate N in the row and potentially be used more efficiently. While this seems logical in theory, N loss data does not support it. With total N loss very low in 1993 it is difficult to interpret any patterns or effects between fertilizer treatments. The larger leaching numbers for 1994 make patterns more obvious. It can be noted that losses from the furrow area are similar for both treatments during both periods of the season. The row, on the other hand, shows large reductions in the fertigated plots over the conventional during both the erect part of the season as well as the slumped period. A possible theory to explain this is that since less solid N was applied to the fertigated plots there was less available for loss. In other words, the fertigation treatment with reduced starter N and delayed applications based on plant need succeeded in reducing N loss to groundwater. It is possible that the furrow would have had less loss had fertigation not been applied, but overall N loss was still reduced, so the use of sap-test based fertigation can be viewed as a success.

Inspection of the N budget shows very large discrepancies between measured use and loss factors. These discrepancies exceeded 75% of total applied N in some instances indicating that there were some factors which were not accounted for. One possible source of error is that there are some N sinks that were not considered with the budgets. First, there was no measure of N which was tied up in plant roots. In addition, some N may have been tied up by the organic fraction of the soil, and therefore was not extracted. A final source of error could have been volatilization of ammonium from either the soil surface, or from the plants. Regardless of the source of error one should note that had Leaching been determined by subtracting out other known factors the results would have been very different from those actually measured.

In summary, water loss depends on row position. Using a fertilization scheme that utilizes fertigation during the tuber bulking stage may lead to less N loss from leaching. Comparisons of positional differences in N loss need to take both water loss and soil water nitrate concentration into consideration. Comparison of different fertilizer management schemes by looking at only one row position has some risk as to accuracy. The accuracy of measuring total N losses, or estimating loss by using N budgets is questionable, but assuming common error, either method allows for a valid comparison between treatments.

References

Association of Official Analytical Chemists (AOAC). 1970. Official methods of analysis of the Association of Official Analytical Chemists. 11th ed. Association of Official Analytical Chemists, Washington, D.C.

Biggar, J.W., and D.R. Neilsen. 1976. Spatial variability of the leaching characteristics of a field soil. Water Resour. Res. 12:78-84.

Campbell, G.S. 1982. Modeling Soil Physics With Basic. ?ed. Publisher, City, state.

Carlson, B.M. 1995. Water distribution patterns under a potato canopy. M.S. diss. Univ. of Minnesota, St. Paul.

Carlson, R.M. 1978. Automated separation and conductimetric determination of ammonia and dissolved carbon dioxide. Anal. Chem. 50:1528-1531.

Carlson, R.M., R.I. Cabrera, J.L. Paul, J. Quick, and R.Y. Evans. 1990. Rapid direct determination of ammonium and nitrate in soil and plant tissue extracts. Commun. Soil Sci. Plant Anal. 21:1519-1529.

Edwards, D.M., P.E. Fischbach and L.L. Young. 1972. Movement of nitrates under irrigated agriculture. Trans. Am. Soc. Agric. Eng. p.73-75.

Endelman, F.J., D.R. Keeney, J.T. Gilmour, and P.G. Saffigna. 1974. Nitrate and chloride movement in the Plainfield loamy sand under intensive irrigation. J. Environ. Qual. 3:295-298.

Knox, and Moody.

Lauer, D.A. 1985. Nitrogen uptake patterns of potatoes with high-frequency sprinkler-applied N fertilizer. Agron. J. 77:193-197.

Milburn, P., J.E. Richards, C. Gartley, T. Pollack, H. O'Neill, and H. Bailey. 1990. Nitrate leaching from systematically tiled potato fields in New Brunswick, Can. J. Environ. Qual. 19:448 - 454.

Neeteson, J.J. 1989. Effect of reduced fertilizer nitrogen application rates on yield and nitrogen recovery of sugar beet and potatoes. Neth. J. Agric. Sci. 37:237 - 256.

Nielsen, E.G., and L.K. Lee. 1987. The Magnitude and Costs of Groundwater Contamination From Agricultural Chemicals. Agricultural Economic Rep. No. 576, U.S.D.A.

Ojala, J.C., J.C. Stark, and G.E. Kleinkopf. 1990. Influence of irrigation and nitrogen management on potato yield and quality. Am. Potato J. 67:29-43.

Painter, C.G., and J. Augustin. 1976. The effect of soil moisture and nitrogen on yield and quality of the russet burbank potato. Am. Potato J. 53:275-284.

Reece, C.F. and B.M. Carlson. 1994. Positional infiltration and root water uptake under a potato canopy using TDR. p.22. *In* Agronomy Abstracts. ASA, Madison WI.

Roberts, S., W.H. Weaver and J.P. Phelps. 1982. Effect of rate and Time of fertilization on nitrogen and yield of russet burbank potatoes under center pivot irrigation. Am. Potato J. 59:77-86.

Rosen, C.J. 1992. Potato Best Management Practices. 1995. Report to Legislative Commission on Minnesotas Resources.

Rosen, C.J. and M.J. Errebbi. 1993. A Field Sap Test for Determining Petiole Nitrate - Nitrogen. Proc. Wisconsin Annual Potato Meetings. p105-108.

Saffigna, P.G., D.R. Keeney, and C.B. Tanner. 1977. Nitrogen, chloride, and water balance with irrigated russet burbank potatoes in a sandy soil. Agron. J. 69:251-257.

Saffigna, P.G., C.B. Tanner, and D.R. Keeney. 1976. Non-uniform infiltration under potato canopies caused by interception, stemflow, and hilling. Agron. J. 68:337-342.

Sexton, B.T. 1993. Influence of Nitrogen and Irrigation Management on Corn and Potato Response and Nitrate Leaching. M.S. diss. Univ. of Minnesota, St. Paul.

Wagenet, J. Average concentration method

Wright, J.A. and F. Bergsrud. 199?. The Checkbook Method of Irrigation Scheduling. Minnesota Extension Service.

List of Figures

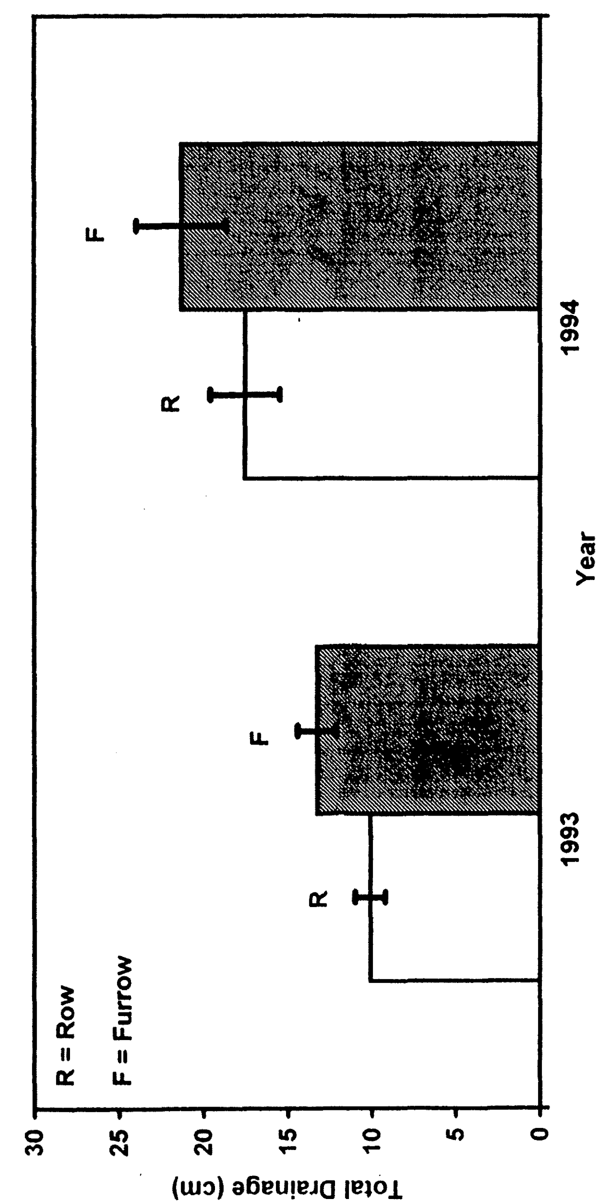
Figure 1. Cumulative drainage from the row and furrow positions for 1993 and 1994. Error bars represent one standard error.

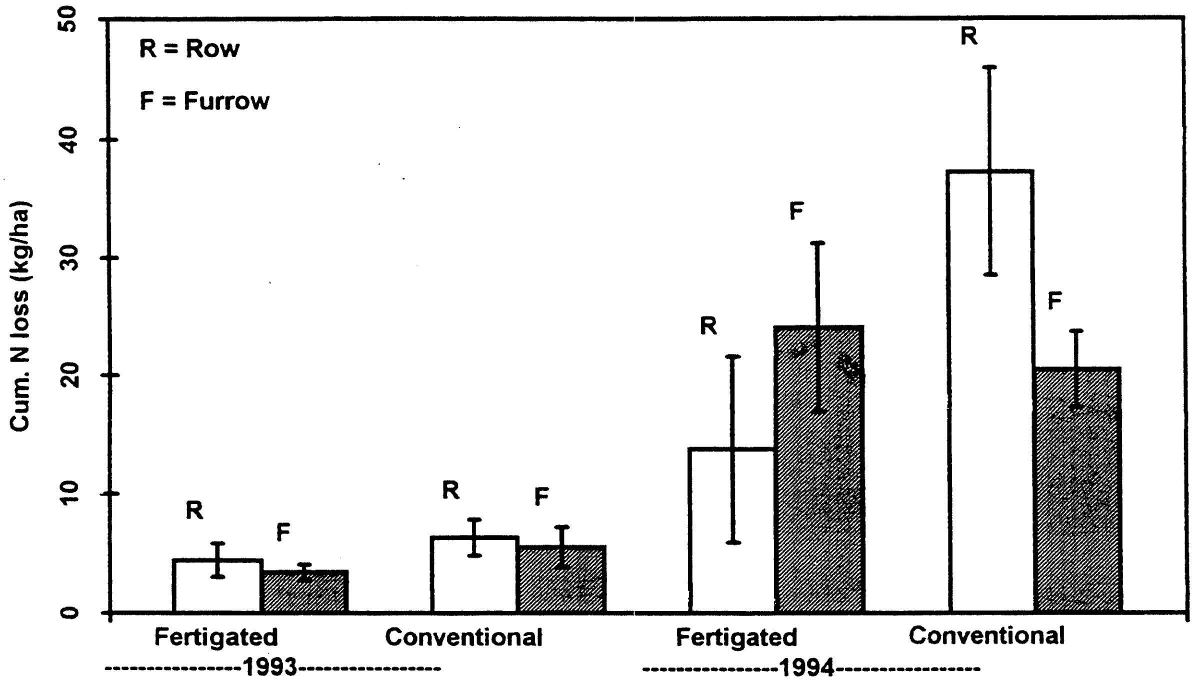
Figure 2. Cumulative N loss calculated from water drainage and soil water nitrate concentrations. Error bars equal one standard error.

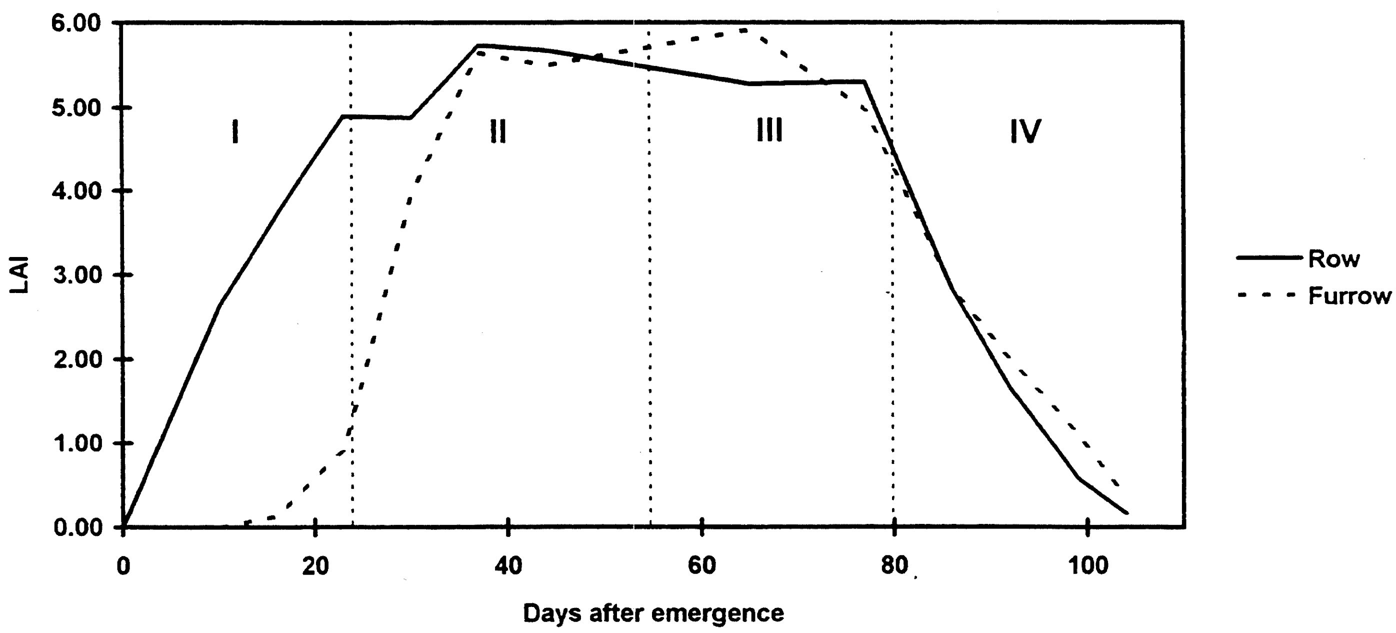
Figure 3. Leaf Area Index for a sample year / treatment combination (other year / treatment combinations followed similar patterns). The four sections represent the stages of the plant canopy. Section I is the initial growth stage. Section II has a full, upright canopy. Section III is the full, slumped canopy. Section IV is senescence.

Figure 4. Cumulative N leaching for the upright and slumped canopy periods for both study years. Error bars represent one standard error.

Table 1. Components of the nitrogen budget. Values are in kg N/ha




R = Row
F = Furrow
Cum. N loss (kg/ha)
0
10
20
30
40
50
R
F
Fertigated
Conventional
----------------1993----------------
----------------1994----------------


LAI
0.00
1.00
2.00
3.00
4.00
5.00
6.00
I
II
III
IV
0
20
40
60
80
100
Days after emergence
Row
Furrow

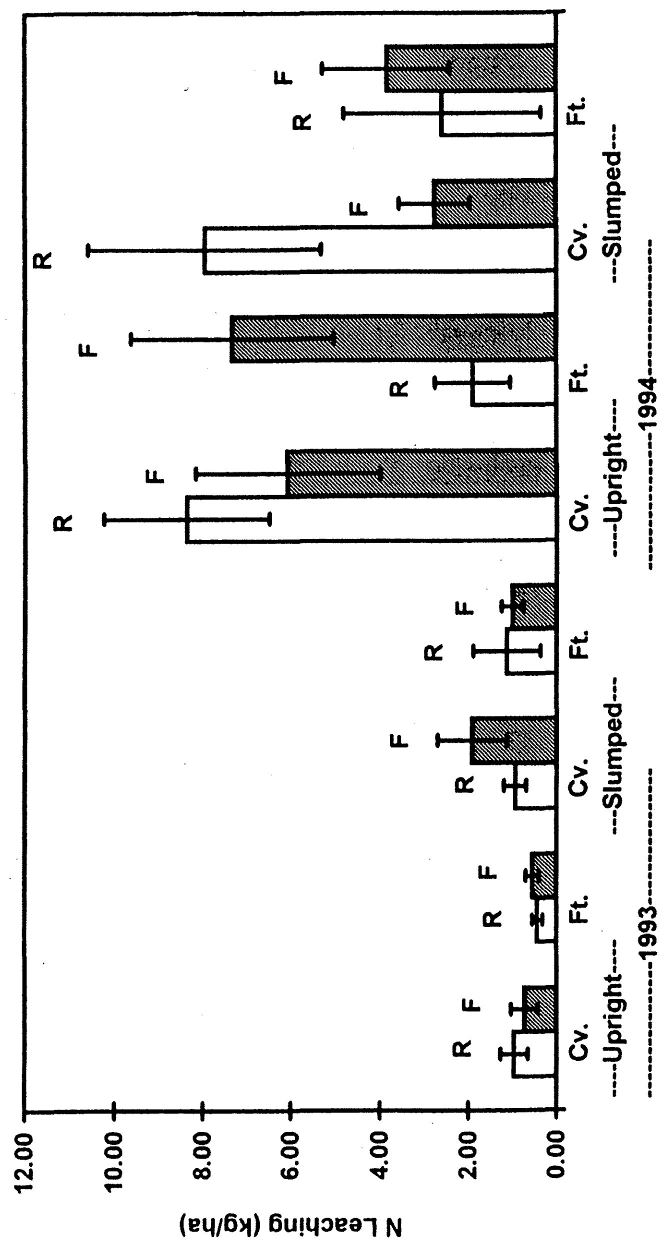


Table 1.

	Conventional	Fertigated	Conventional	Fertigated
	------------1993-----------		------------1994------------	
Initial Soil N	38.12	37.87	57.50	50.53
Plant and Tuber Uptake	126.62	150.30	183.01	180.25
Measured Leaching	4.41	2.91	21.44	14.05
Residual Soil N	15.91	16.46	30.15	28.40
Discrepancy	204.50	159.12	141.89	146.80

Irrigated Potato Nitrogen Management Demonstrations at Park Rapids and Becker - Detailed Report, Objective C.1. (part 2)

Specific objective: To demonstrate the effects of improved N management strategies on potato yield and nitrate movement under field conditions.

Procedures: Improved N management strategies were demonstrated in growers fields during the 1993 and 1994 growing seasons. In 1993, two potato pivots (Becker South and Westrum Farms) near Park Rapids (Hubbard County) and one potato pivot (K and O Farms) near Becker (Sherburne County) were monitored. In 1994, one potato pivot (Victor Farm) near Park Rapids and one (K and O Farms) near Becker were monitored. Russet Burbank was the potato cultivar used in all demonstrations. The original plan was to manage half of each field according to conventional grower procedures and the other half using improved N management strategies. The improved strategies included: reduced N at planting (< 40 lb N/A), reduced N at emergence (70-90 lb N/A), reduced N at hilling (70-90 lb N/A), post-hilling N applications would be based on the sap test. In the past, conventional grower procedures included 60 to 100 lb N/A at planting, and 80 to 100 lb N/A at emergence and hilling. Post-hilling applications were not usually based on any diagnostic criteria. Unfortunately, we were unable to get the growers to follow these conventional procedures in our demonstrations. Growers more or less mimicked the improved management practices on both sides of the field. There were only minor differences in N management between either side of the field. The demonstrations were still useful because other growers in the areas were made aware that these improved practices did not detrimentally affect yield and quality.

Suction tubes were installed the day after planting in both sides of each field at the 4.5 ft depth both in the row and between the row. Four to six replications were used on each side of the field. Soil water was collected on a weekly basis or whenever rainfall exceeded 0.5". Petiole sap samples were collected and nitrate was determined using portable Cardy nitrate electrodes. Communication with the grower was established to determine when to apply nitrogen. At harvest, vine and tuber weight were recorded from four to six 20 ft rows. Tubers were graded by hand and then weighed. Subsamples of vine and tuber were taken for dry matter determination. Other measurements included initial soil nitrate (0-2'), post-harvest soil nitrate (0-2'), rainfall, N uptake in vines and tubers. Two field corn fields (Buck Farm, 1993 and Becker South Farm, 1994) in Park Rapids were also monitored for nitrate movement to compare with the potato fields.

Plot plans along with specific N timing and application rates for each demonstration are provided in Figures 1-6. The field corn demonstration at the Buck Farm in Park Rapids in 1993 is not shown, but the set up is similar to the field corn demonstration at the Becker South Farm in 1994 (Figure 6).

Results: In 1993, total potato yields were similar or slightly higher for the sap based (improved) N management (Tables 1-3). In two of the three fields, tuber size increased with the improved management and in the other tuber size was slightly lower. Specific gravity was generally higher with the improved practice. Sap nitrate levels through the season for the three fields are presented in Figures 7-9. Using criteria established in Objective B, the sap test seemed to work reasonably well for predicting when additional N is needed (or not needed). An example where the sap test worked ideally was in the Becker, K and O Farm where the nitrate level dropped to critical levels on both sides of the field. Nitrogen was applied once at 30 lb N/A. The sap petiole level increased to sufficient levels and remained in the optimum range for the rest of the season. Nitrogen uptake in vines and tubers is presented in Tables 4-6. In general, uptake of N in vines and tubers followed yield. Nitrate concentrations at the 4.5 ft depth as measured by suction tubes were lower in two out of the three fields tested (Figures 10-12). Large differences in nitrate concentrations were not observed because differences in rates and timing were not that different. For comparison, one field near Park Rapids (Buck Farm) included monitoring nitrate concentrations in a field of irrigated corn (Figure 13). In this field, nitrogen was applied at a rate of 160 lbs N/A (12 lb N/A starter and 148 lb N/A as anhydrous sidedress). The yield for this field was 109 bu/A. Under the cool conditions of 1993, nitrate leaching in the irrigated corn field was similar to nitrate leaching in irrigated potatoes when best management practices were used. Residual soil nitrate at harvest, on average, tended to be higher in the sap based treatment compared to the more conventional treatment (Tables 7-9). This may be due to higher rates of N applied later in the season. The practice of using a cover crop after harvest will be necessary to help prevent residual nitrate from leaching to ground water.

In 1994, insect and disease pressure caused poor tuber size at the Becker K and O site (Table 10). In addition, nitrate concentrations in the sap were at critical levels early, possible due to over irrigation (Figure 14). Trends in soil water nitrate-N at the 4.5 ft depth in this field were not conclusive with concentrations initially higher in the grower treatment and then higher in the sap based treatment by the end of the season (Figure 16). The N stress and pest pressure resulted in a less than optimum demonstration, but did show that an integrated approach to managing potato production is essential. In Objective E.4, a detailed modelling effort was used to simulate nitrate leaching at the K and O Farm in 1994. The model suggested that over-irrigation was the main cause of N stress and caused significant nitrate leaching. The model and sap tests were useful in predicting N stress. The model was also useful in suggesting possible reasons for the N stress. At the Park Rapids site in 1994, there was little difference between the two treatments in yield or quality (Table 11). Petiole sap nitrate concentrations were similar for both treatments and followed the optimum levels established in Objective B (Figure 15). Nitrate concentrations in the soil water at the 4.5 ft depth at the end of the season were higher with the conventional treatment; however, concentrations were higher with the sap-based treatment at mid-season (Figure 17). The increase in nitrate levels in this field was associated with 4 inches of rain at six weeks after planting. The corn field monitored near Park Rapids in 1994 had slightly lower nitrate concentration in the soil water compared to potatoes managed with improved N practices (Figure 18). Nitrogen uptake in vines and tubers is presented in Tables 12 and 13. In general, there was little difference between the two treatments in N uptake. Residual soil nitrate was slightly higher in the sap based treatment at the Becker site, but there was no difference at the Park Rapids site (Tables 14 and 15).

General Summary and Conclusions: A summary of the effects of sap based versus conventional N management on potato yield and quality, N uptake, and residual soil N is presented Table 16. As mentioned above, differences in N application timing between the two treatments were not as great as hoped, but still provide useful information for a demonstration. The total amount of N applied on the conventional side was about 270 lb N/A compared to 240 lb N/A on the sap based side. The lower amount of N applied coupled with more appropriate N timing did not detrimentally affect yield or quality. From an economic stand point lower N applications would save the farmers $600 in a 100 acre field which would more than offset the cost of petiole sap analysis. Since N uptake between the two treatments is the same, N use efficiency in the sap based treatment is generally improved. Residual soil nitrate tended to be higher in the sap based treatments and indicate the need to plant a cover crop shortly after the potatoes are harvested. While nitrate leaching as measured by suction tubes was not conclusive in these demonstrations, the reduction in fertilizer N inputs coupled with proper timing suggest that overall leaching will be reduced. The demonstrations were very effective in showing growers that N management practices can be improved without detrimental effects on yield and quality. Use of the demonstrations and field experiments from objectives B and C has resulted in the development of Nitrogen Best Management Practices for irrigated potatoes. The suggested BMPs developed have been sent out to growers for discussion and once the final revision is made, the BMPs will be adopted for use by the Minnesota Department of Agriculture and other state agencies.

Table 1. Effect of nitrogen management on potato yield and quality at K and O, Becker, MN - 1993.

Treatment	Knobs	<6 oz	6-13 oz	>13 oz	Total	Specific Gravity	Hollow Heart
	cwt/A						- % -
Conventional	33 ± 4	217 ± 47	255 ± 43	11 ± 8	516 ± 30	1.0846 ± 0.0018	2.0 ± 2.2
Sap based	24 ± 13	201 ± 29	299 ± 65	32 ± 28	556 ± 75	1.0885 ± 0.0020	1.3 ± 2.1

Table 2. Effect of nitrogen management on potato yield and quality at Westrom, Park Rapids, MN - 1993.

Treatment	Knobs	<6 oz	6-13 oz	>13 oz	Total	Specific Gravity	Hollow Heart
	cwt/A						- % -
Conventional	15 ± 3	207 ± 33	194 ± 14	2 ± 3	418 ± 29	1.0874 ± 0.0021	10.7 ± 2.3
Sap based	30 ± 11	208 ± 42	201 ± 32	4 ± 7	444 ± 36	1.0890 ± 0.0008	5.3 ± 6.1

Table 3. Effect of nitrogen management on potato yield and quality at Becker South, Park Rapids, MN - 1993.

Treatment	Knobs	<6 oz	6-13 oz	>13 oz	Total	Specific Gravity	Hollow Heart
	cwt/A						- % -
Conventional	44 ± 33	187 ± 21	247 ± 63	7 ± 10	485 ± 34	1.0874 ± 0.0013	8.0 ± 5.7
Sap based	19 ± 9	239 ± 32	225 ± 28	2 ± 4	485 ± 17	1.0882 ± 0.0013	11.3 ± 5.3

Table 4. Effect of nitrogen management on nitrogen content and dry matter production. K and O, Becker, MN - 1993.

Treatment	Nitrogen Content			N Concentration		Dry Matter		
	Vines	Tubers	Total	Vines	Tubers	Vines	Tubers	Total
	lbs/A			% N		tons/A		
Conventional	26.8	153.5	180.3	1.71	1.44	0.93	5.32	6.25
Sap based	25.7	164.5	190.2	1.40	1.35	0.96	6.14	7.10

Table 5. Effect of nitrogen management on nitrogen content and dry matter production. Westrom, Park Rapids, MN - 1993.

Treatment	Nitrogen Content			N Concentration		Dry Matter		
	Vines	Tubers	Total	Vines	Tubers	Vines	Tubers	Total
	lbs/A			% N		tons/A		
Conventional	38.8	132.8	171.6	2.53	1.42	0.78	4.69	5.47
Sap based	25.2	121.4	146.6	1.97	1.27	0.64	4.80	5.44

Table 6. Effect of nitrogen management on nitrogen content and dry matter production. Becker South Park Rapids, MN - 1993.

Treatment	Nitrogen Content			N Concentration		Dry Matter		
	Vines	Tubers	Total	Vines	Tubers	Vines	Tubers	Total
	lbs/A			% N		tons/A		
Conventional	44.4	116.8	161.2	2.30	1.15	0.96	5.08	6.04
Sap based	29.9	134.7	164.6	1.80	1.33	0.80	5.07	5.87

Table 7. Initial and end of growing season soil nitrate nitrogen to 3 feet, K and O, Becker, MN - 1993.

Treatment	Depth in feet					
	Initial soil NO_3 - N			End of season NO_3 - N		
	0 - 1	1 - 2	2 - 3	0 - 1	1 - 2	2 - 3
	lbs/A			lbs/A		
Conventional	3.0 ± 1.0	2.7 ± 0.9	2.1 ± 1.2	16.3 ± 3.9	13.0 ± 2.4	9.5 ± 1.0
Sap based	4.4 ± 1.0	3.2 ± 1.3	2.4 ± 1.5	19.8 ± 6.7	13.0 ± 3.2	6.8 ± 2.4

Table 8. Initial and end of growing season soil nitrate nitrogen to 4 feet, Westrom's, Staples, MN - 1993.

Treatment	Depth in feet							
	Initial soil NO_3 - N				End of season NO_3 - N			
	0 - 1	1 - 2	2 - 3	3 - 4	0 - 1	1 - 2	2 - 3	3 - 4
	lbs/A				lbs/A			
Conventional	4.7 ± 2.2	3.7 ± 2.5	2.1 ± 1.6	2.9 ± 2.9	17.9 ± 3.0	5.7 ± 1.2	3.8 ± 1.8	1.9 ± 0.8
Sap based	3.6 ± 1.7	3.0 ± 2.0	1.6 ± 1.0	2.0 ± 0.6	43.8 ± 18.0	9.6 ± 5.1	8.0 ± 8.2	2.6 ± 1.6

Table 9. Initial and end of growing season soil nitrate nitrogen to 4 feet, Becker south, MN - 1993.

Treatment	Depth in feet							
	Initial soil NO_3 - N				End of season NO_3 - N			
	0 - 1	1 - 2	2 - 3	3 - 4	0 - 1	1 - 2	2 - 3	3 - 4
	lbs/A				lbs/A			
Conventional	2.8 ± 1.2	2.4 ± 1.3	1.2 ± 0.6	2.3 ± 1.3	16.5 ± 6.1	8.2 ± 5.5	5.1 ± 4.5	4.6 ± 4.1
Sap based	2.4 ± 1.4	1.6 ± 0.9	0.6 ± 0.4	1.5 ± 0.6	20.6 ± 7.6	5.6 ± 4.6	2.7 ± 1.4	1.1 ± 0.5

Table 10. Effect of nitrogen management on potato yield and quality at K and O, Becker, MN - 1994.

Treatment	<3 oz & Knobs	3-6 oz	6-13 oz	>13 oz	Total	Specific Gravity	Hollow Heart
	cwt/A						- % -
Conventional	1 ± 2	298 ± 28	180 ± 21	10 ± 8	489 ± 42	1.0888 ± 0.0007	2.0 ± 4.0
Sap based	8 ± 9	270 ± 29	187 ± 25	17 ± 10	482 ± 41	1.0861 ± 0.0022	2.0 ± 2.3

Table 11. Effect of nitrogen management on potato yield and quality at Victor, Park Rapids, MN - 1994.

Treatment	Knobs	<3 oz	3-6 oz	6-13 oz	>13 oz	Total	Specific Gravity	Hollow Heart
	cwt/A							%
Conventional	7 ± 6	69 ± 18	206 ± 5	245 ± 20	7 ± 9	534 ± 21	1.0889 ± 0.0015	4.0 ± 5.7
Sap based	5 ± 6	43 ± 11	182 ± 63	254 ± 48	11 ± 7	495 ± 79	1.0894 ± 0.0038	1.6 ± 2.2

Table 12. Effect of nitrogen management on nitrogen content and dry matter production. K and O, Becker, MN - 1994.

Treatment	Nitrogen Content			N Concentration		Dry Matter		
	Vines	Tubers	Total	Vines	Tubers	Vines	Tubers	Total
	lbs/A			% N		tons/A		
Conventional	12.2	156.3	168.5	1.61	1.40	0.37	5.59	5.96
Sap based	9.8	150.6	160.4	1.64	1.40	0.29	5.41	5.70

Table 13. Effect of nitrogen management on nitrogen content and dry matter production. Victor, Park Rapids, MN - 1994.

Treatment	Nitrogen Content			N Concentration		Dry Matter		
	Vines	Tubers	Total	Vines	Tubers	Vines	Tubers	Total
	lbs/A			% N		tons/A		
Conventional	49.7	151.0	200.7	2.08	1.31	1.21	5.88	7.09
Sap based	59.3	139.2	198.5	2.06	1.23	1.42	5.83	7.25

Table 14. Initial and end of growing season soil nitrate nitrogen to 3 feet, K and O, Becker, MN - 1994.

Treatment	Depth in feet: Initial soil NO_3 - N			End of season NO_3 - N
	0 - 1	1 - 2	2 - 3	0 - 2
	lbs/A			lbs/A
Conventional	11.5 ± 1.3	12.0 ± 2.2	13.0 ± 0.8	41
Sap based	7.0 ± 2.6	7.3 ± 4.6	6.0 ± 4.0	57

Table 15. Initial and end of growing season soil nitrate nitrogen to 3 feet, Victor, Park Rapids, MN - 1994.

Treatment	Depth in feet: Initial soil NO_3 - N			End of season NO_3 - N		
	0 - 1	1 - 2	2 - 3	0 - 1	1 - 2	2 - 3
	lbs/A			lbs/A		
Conventional	27.2 ± 12.3	17.9 ± 2.7	7.6 ± 1.7	15.4 ± 5.2	4.7 ± 1.6	6.4 ± 3.9
Sap based	24.4 ± 10.2	10.4 ± 3.4	6.8 ± 0.8	14.4 ± 4.4	6.5 ± 4.4	3.1 ± 2.0

Table 16. Summary comparison of sap based N management with conventional N management. Effects on potato yield and quality, N uptake, and residual soil N. Average of five potato demonstrations over the 1993 and 1994 growing seasons.

Parameter	Sap based	Conventional
N applied (lb/A)	238	271
Total yield (cwt/A)	492	488
6-13 oz yield (cwt/A)	233	224
Specific gravity	1.0882	1.0874
Vine N content (lb N/A)	30	34
Tuber N content (lb N/A)	142	142
Total N uptake (lb N/A)	172	176
Residual soil nitrate (lb N/A, 0-2ft)	38	28

1993 K & O

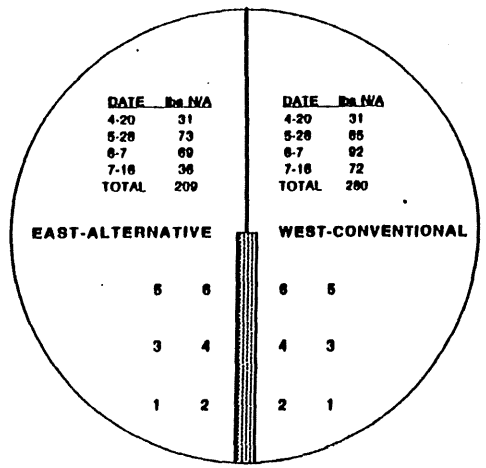


Figure 1. Potato nitrogen demonstration at K and O Farms, Becker, MN, 1993. Previous crop was soybean.

1993 WESTROM

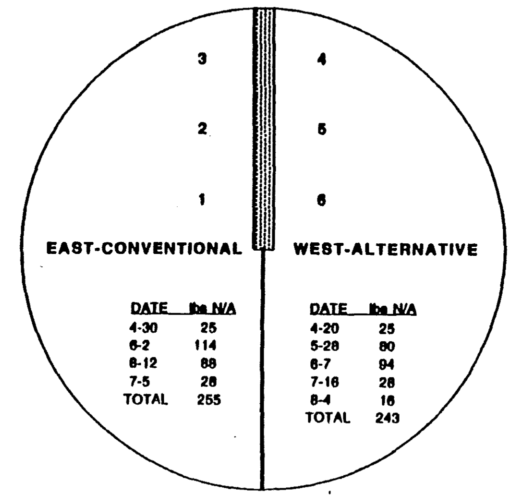


Figure 3. Potato nitrogen demonstration at Westrum Farm, Park Rapids, MN, 1993. Previous crop was kidney bean.

1993 BECKER SOUTH

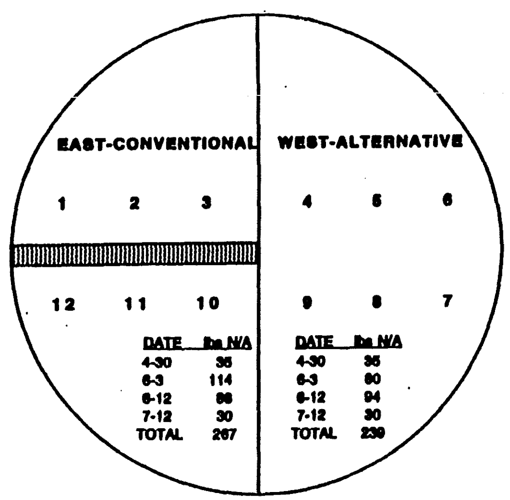


Figure 2. Potato nitrogen demonstration at Becker South Farm, Park Rapids, MN, 1993. Previous crop was kidney bean.

1994 BECKER - K & O (POTATOES)

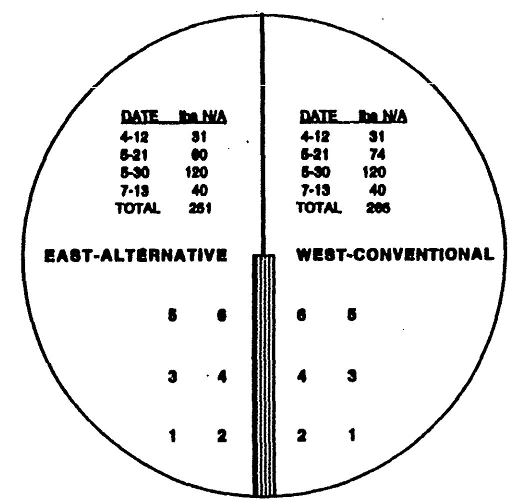


Figure 4. Potato nitrogen demonstration at K and O Farm, Becker, MN, 1994. Previous crop was seed corn.

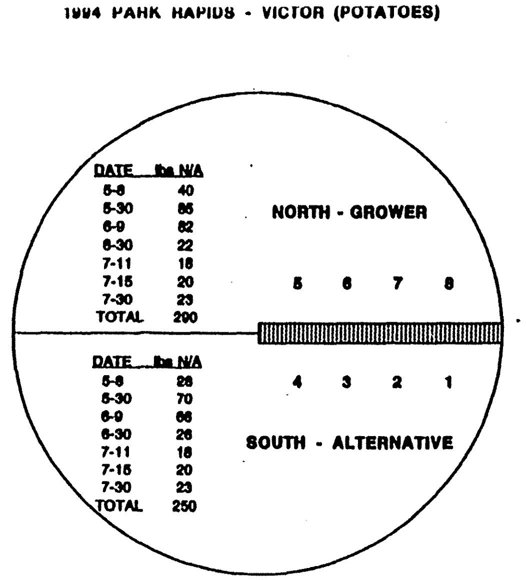


Figure 5. Potato nitrogen demonstration at Victor Farm, Park Rapids, MN, 1994. Previous crop was kidney bean.

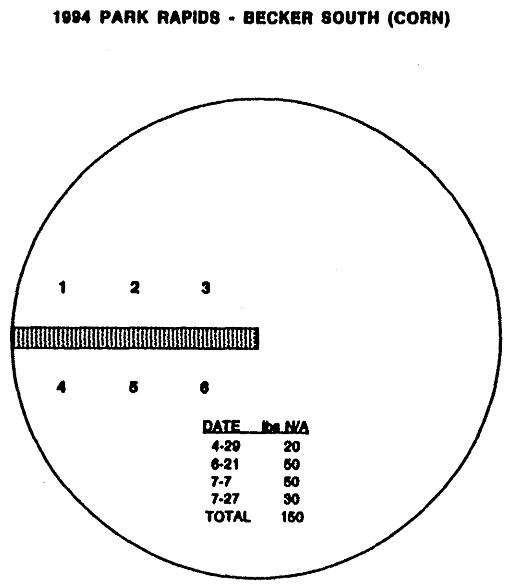


Figure 6. Corn nitrogen demonstration at Becker South Farm, Park Rapids, MN, 1994. Previous crop was potato.

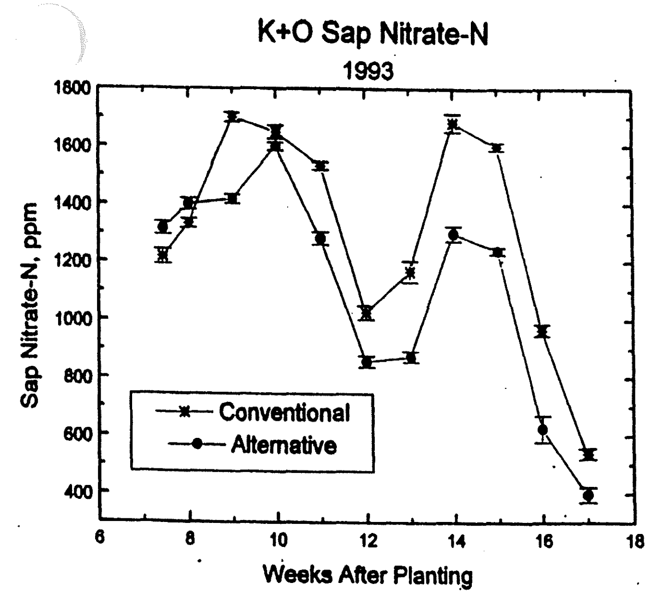


Figure 7. Sap nitrate-N levels in potato petioles through the growing season. K and O Farms, Becker, MN, 1993.

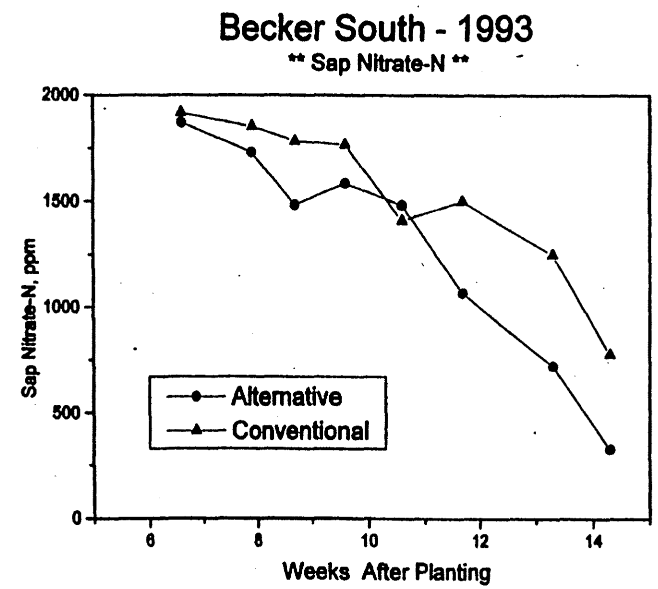


Figure 8. Sap nitrate-N levels in potato petioles through the growing season. Becker South Farm, Park Rapids, MN, 1993.

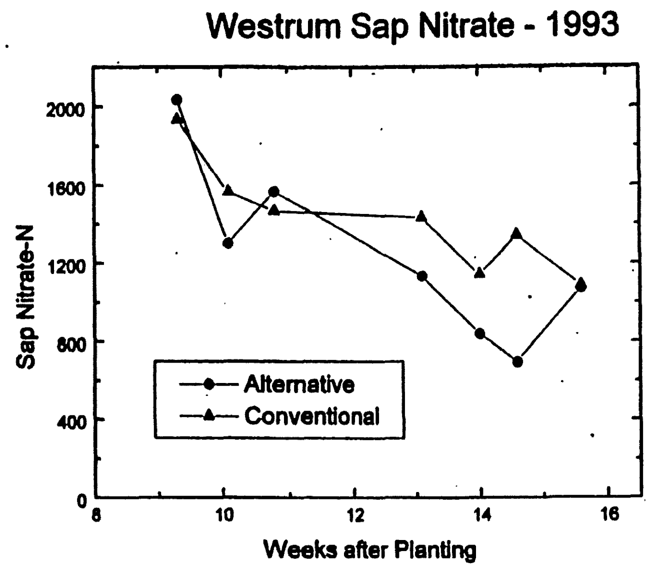


Figure 9. Sap nitrate-N levels in potato petioles through the growing season. Westrum Farm, Park Rapids, MN, 1993.

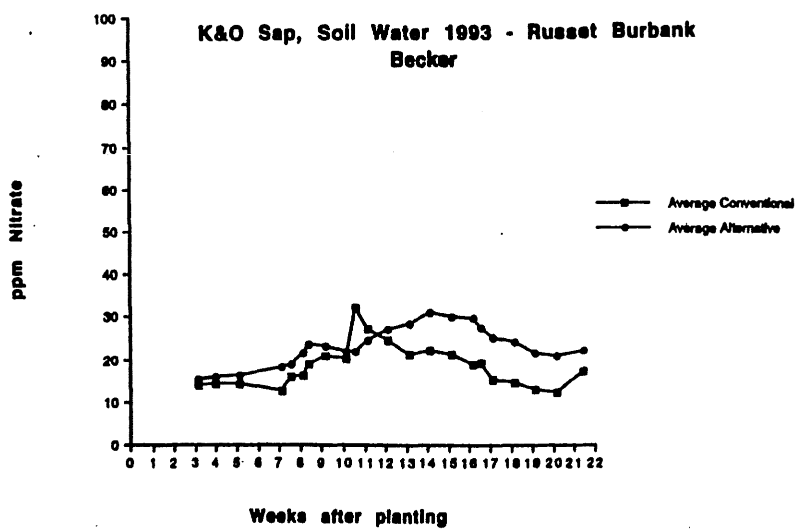


Figure 10. Nitrate-N concentrations in the soil water at the 4.5 ft depth through the growing season - potatoes. K and O Farms, Becker, MN, 1993.

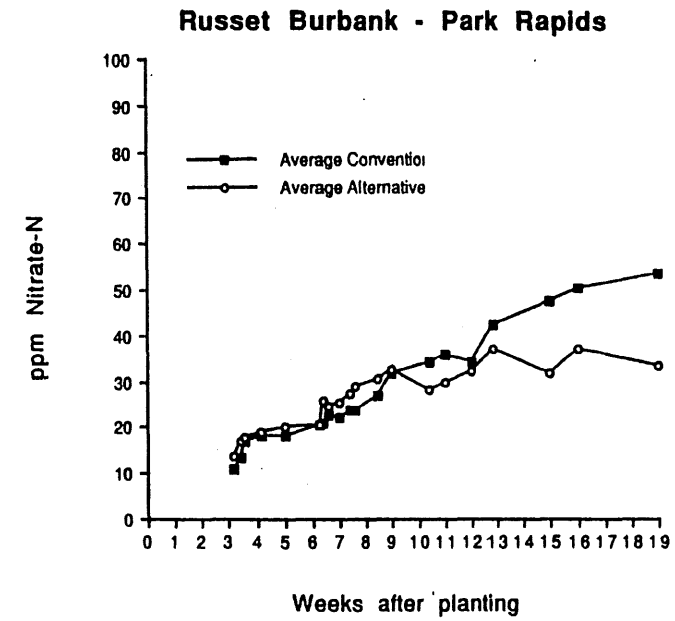


Figure 11. Nitrate-N concentrations in the soil water at the 4.5 ft depth through the growing season - potatoes. Becker South Farm, Park Rapids, MN, 1993.

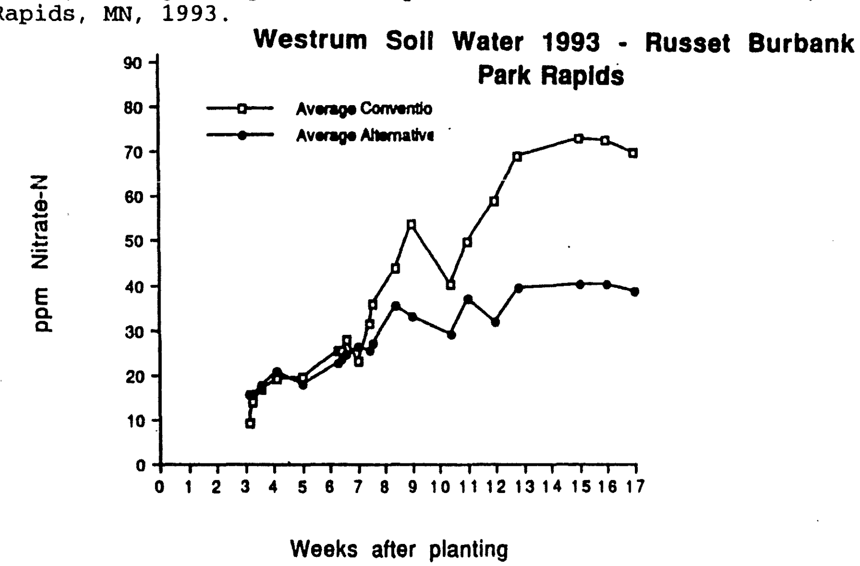


Figure 12. Nitrate-N concentrations in the soil water at the 4.5 ft depth through the growing season - potatoes. Westrum Farm, Park Rapids, MN, 1993.

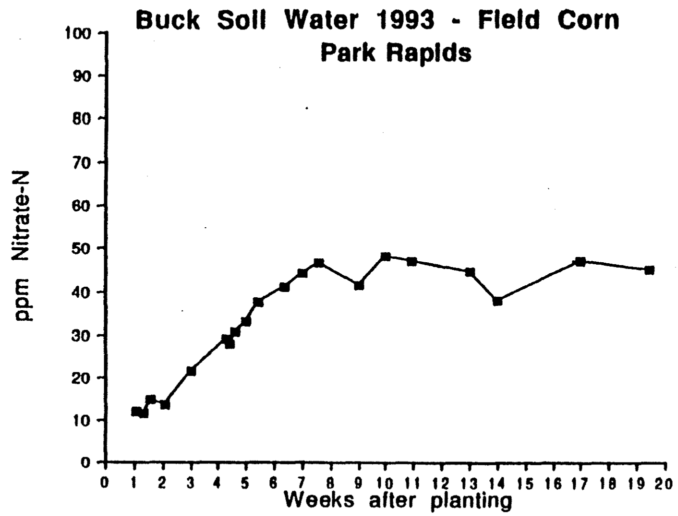


Figure 13. Nitrate-N concentrations in the soil water at the 4.5 ft depth through the growing season - corn. Buck Farm, Park Rapids, MN, 1993.

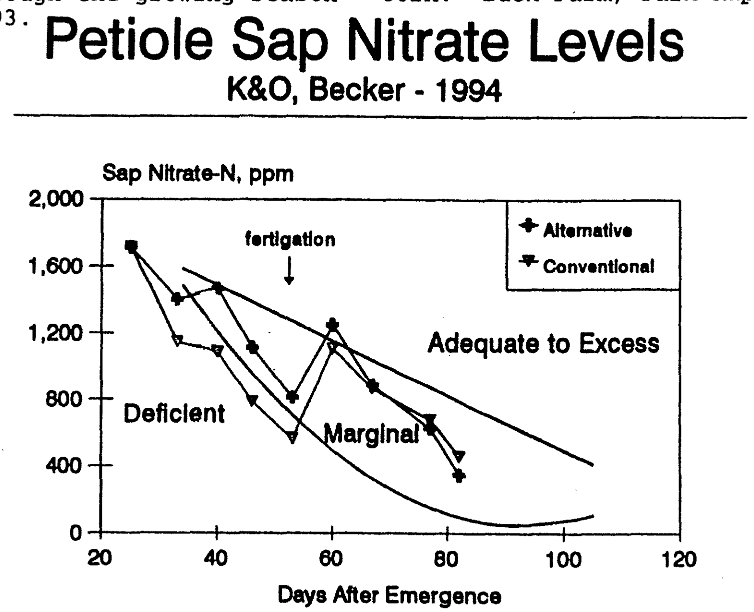


Figure 14. Sap nitrate-N levels in potato petioles through the growing season. K and O Farms, Becker, MN, 1994.

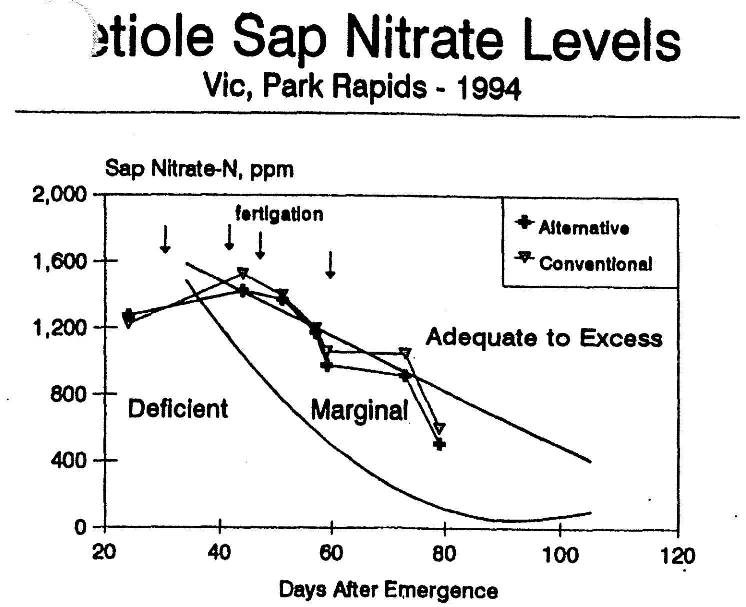


Figure 15. Sap nitrate-N levels in potato petioles through the growing season. Victor Farm, Park Rapids, MN, 1994.

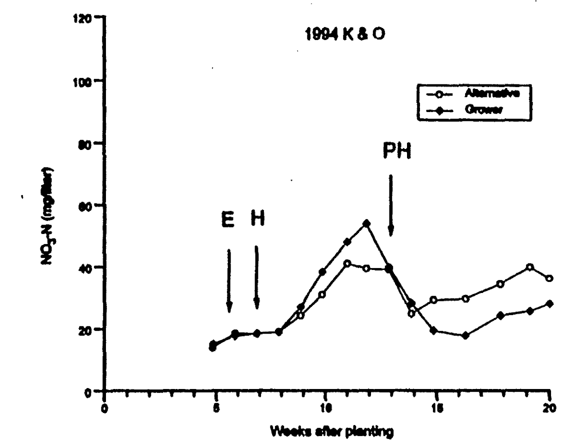


Figure 16. Nitrate-N concentrations in the soil water at the 4.5 ft depth through the growing season - potatoes. K and O Farms, Becker, MN, 1994.

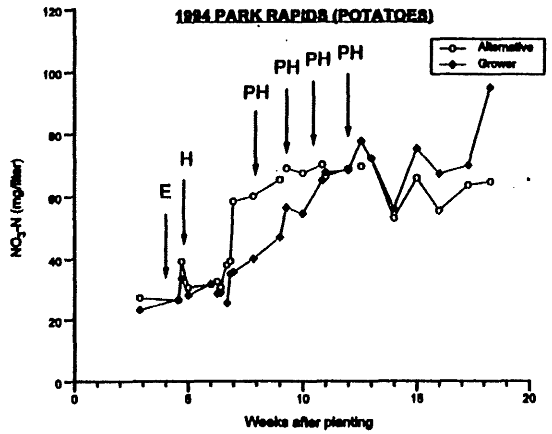


Figure 17. Nitrate-N concentrations in the soil water at the 4.5 ft depth through the growing season - potatoes. Victor Farm, Park Rapids, MN, 1994.

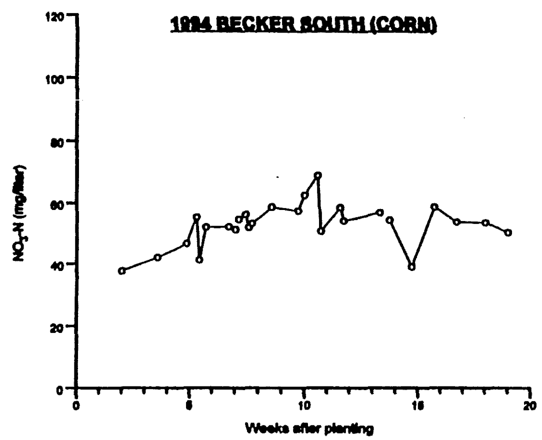


Figure 18. Nitrate-N concentrations in the soil water at the 4.5 ft depth through the growing season - corn. Becker South Farm, Park Rapids, MN, 1994.

BEST MANAGEMENT PRACTICES FOR NITROGEN USE: IRRIGATED POTATOES

Carl J. Rosen
Department of Soil Science
University of Minnesota

Introduction

Nitrogen (N) is an essential plant nutrient that is applied to Minnesota crops in greater quantity than any other fertilizer. In addition, vast quantities of N are contained in the ecosystem, including soil organic matter. Biological processes that convert N to its mobile form, nitrate (NO_3), occur continuously in the soil system. (For greater understanding see: Understanding Nitrogen in Soils AG-FO-3770). Unfortunately, nitrate can move (leach) below the rooting zone and into groundwater.

In response to the Comprehensive Groundwater Protection Act of 1989, a Nitrogen Fertilizer Management Plan was developed with the purpose of managing N inputs for crop production to prevent degradation of Minnesota water resources while maintaining farm profitability. The central tool for achievement of this goal is the adoption of Best Management Practices (BMPs) for Nitrogen. Best management practices for N are broadly defined as economically sound, voluntary practices that are capable of minimizing nutrient contamination of surface and groundwater. The primary focus of the BMPs is commercial N fertilizers; however, consideration of other N sources and their associated agronomic practices is necessary for effective total N management.

Statewide BMPs

The use of BMPs is based on the concept that accurate determination of crop N needs is essential for profitable and environmentally sound N management decisions. General statewide BMPs are listed below and are covered in more detail in Best Management Practices for Nitrogen Use Statewide in Minnesota AG-FO-6125.

* Adjust N rate according to a realistic yield goal and previous crop

* Do not apply N above recommended rates

* Plan N timing to achieve high efficiency of N use

* Develop and use a comprehensive record-keeping system for field specific information.

* If manure is used, adjust N rate accordingly and follow proper manure management procedures to optimize N credit:

- Test manure for nutrient content
- Calibrate manure application equipment, base rate on available N content
- Apply manure uniformly through out a field
- Injection of manure is preferable, especially on steep sloping soils
- Avoid manure application to sloping, frozen soils
- Incorporate broadcast applications whenever possible.

The Need for Best Management Practices for Irrigated Potatoes

Most of the BMPs developed for crop production in Minnesota have been based on research with corn and small grains. Refer to: Best Management Practices for Nitrogen Use Statewide in Minnesota (AG-FO-6125-C) and Best Management Practices for Nitrogen Use on Irrigated, Coarse-textured Soils (AG-FO-6131-B) for more information. In contrast to most agronomic crops, potatoes are a relatively shallow rooted crop and require intensive management to promote growth and yield. In addition, adequate N needs to be available to maintain yield and tuber quality. The shallow root system of potatoes, the need for adequate N, and production on sandy soils greatly increase the potential of nitrate contamination of shallow aquifers under irrigated potato production. Fortunately, University of Minnesota research strongly suggests that environmental impacts can be minimized by using nitrogen BMPs specifically designed for potatoes.

While the general BMPs developed for corn and small grains listed above will also apply to irrigated potato production, BMPs for irrigated potato production are described within this bulletin so that more precise management practices can be followed. The nitrogen BMPs discussed here, therefore, have been tailored specifically for potato production on irrigated coarse-textured soils.

Specific Nitrogen Best Management Practices for Irrigated Potatoes

Nitrogen management considerations for irrigated potatoes include decisions regarding: N rate, timing of N application, use of diagnostic procedures to determine post-hilling N needs, effective water management, sources of N, and establishment of a cover crop after harvest. Suggested N management approaches for irrigated potatoes are presented following the discussion on BMPs.

<u>Selecting a Realistic Nitrogen Rate</u>

The rate of N to apply to irrigated potatoes is dependent on expected yield goal and previous crop. Rates of N recommended for potatoes can be found in Nutrient Management for Commercial Fruit and Vegetable Crops in Minnesota (AG-BU-5886-F). Response to N by potato is typical of other crops in that the first increment usually brings about the greatest response in total yield followed by a more gradual increase (Table 1). As the N rate increases, however, the potential for losses also increase. In addition to environmental concerns due to excessive N applications, high rates of N can detrimentally affect production by promoting excessive vine growth delaying tuber maturity, and inducing knobby/misshapen and hollow tubers. Selecting a realistic N rate is therefore important from a production as well as an environmental standpoint. Unfortunately, the effect of excess N on tuber quality is dependent on soil moisture and temperature as well as cultivar. The N rate at which detrimental effects will occur is difficult to predict.

**** Develop realistic yield goals based on variety and harvest date**

Different potato varieties and differences due to harvest date will have a pronounced effect on yields and yield goals. Because of lower yield and earlier harvest, early maturing varieties such as Norland require less N than later maturing varieties such as Russet Burbank. Yield goal for potatoes is based on total yield obtained rather than marketable yield. An overestimation of the yield goal will result in excessive applications of N, which can potentially result in nitrate losses to groundwater.

**** Account for nitrogen from previous crops**

Previous crop can also affect nitrogen needs. Legumes in a crop rotation can supply some N to subsequent crops. Data from Wisconsin on sandy soils demonstrate the effect of legumes on potato N response

(Table 2). Failing to account for N supplied by legumes can lead to a build up of soil N and increase the potential for nitrate leaching.

Table 1. Potato (Russet Burbank) response in 1991 and 1992 to nitrogen at Becker, MN. Yields averaged over several methods of application.

N rate lb N/A	Marketable	Total
	---------- cwt/A	----------
0	259	322
120	412	498
160	412	504
200	431	527
240	453	543

Table 2. Effect of N rate and previous crop on potato (Russet Burbank) yield. Hancock, WI - 1991[1]

	Previous crop		
N rate	Alfalfa	Red Clover	Sorghum/sudan
lb N/A	----------------	cwt/A	-------------------
0	262	188	107
40	300	207	155
80	332	237	211
120	348	242	246
160	333	264	247
200	326	236	267
240	330	243	268

[1] K. Kelling et al. (1993) Proc. WI Annual Potato Meetings. pp. 93-103.

**** Test irrigation water for nitrogen content and adjust N fertilizer accordingly**

The amount of N in the irrigation water should also be considered when adjusting N rates. Nitrate in irrigation water can supply a significant portion of N for crop production. In N calibration studies on potatoes at Becker, Minn., the nitrate-N concentration in irrigation water ranged from 7 to 10 ppm. This concentration of N in the water should be considered as background. Levels above 10 ppm should be credited as fertilizer N. Additionally, the main time to credit N from irrigation water is when the plant is actively growing and taking up N. For potatoes this occurs from 20 to 60 days after emergence. Because nitrate-N levels in irrigation water can vary, samples of irrigation water need to be tested annually during the pumping season to determine approximate nitrate-N concentrations. One part per million (ppm) of nitrate-N in irrigation water is equal to 0.225 pounds of N applied per acre with each inch of irrigation water applied. As an example, if irrigation water is found to have 20 ppm nitrate-N and 9 inches of water are applied during the active part of the growing season, then 40 lbs of N would be supplied with the water, 20 of which should be credited toward the total amount of N applied.

Timing of Nitrogen Application: Match Nitrogen Application with Demand by the Crop

One of the most effective methods of reducing nitrate leaching losses is to match N application with N demand by the crop.

**** Do not fall apply N on sandy soils**
**** Do not use more than 40 lbs N/A in the starter**
**** Nitrogen applied through the hilling stage should be cultivated/incorporated into the hill**
**** Plan the majority of N inputs from 10 to 50 days after emergence**

Nitrogen applications in the fall are very susceptible to leaching. Nitrogen applied early in the season when plants are not yet established is also susceptible to losses with late spring and early summer rains. Most nitrification inhibitors are not registered for potatoes and therefore cannot be recommended. Peak N demand and uptake for late season potatoes occurs between 20 and 60 days after emergence (Figure 1).

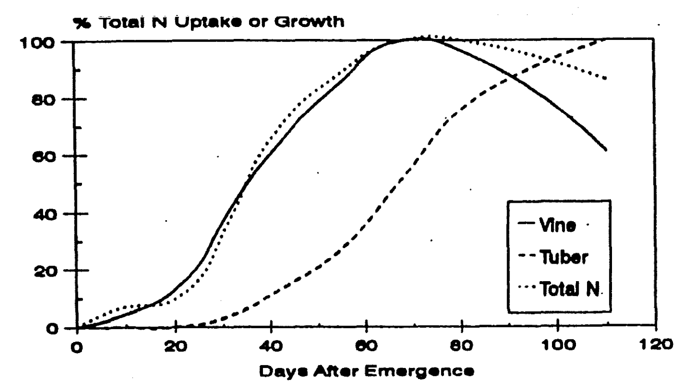


Figure 1. Relative tuber growth, vine growth, and total nitrogen uptake by the potato crop.

Optimum potato production is dependent on having an adequate supply of N during this period. The recommendation to apply N earlier slightly before (by 10 days) the optimum uptake period is to assure that adequate N is available at the time the plant needs it.

Research at the Sand Plain Research Farm at Becker demonstrates nitrate movement below the root zone can be reduced by lowering the amount of N in the starter fertilizer without affecting yields (Tables 3 and 4; Figures 2A and 2B). Uptake of N by the crop (vines plus tubers) is increased when split N applications are used compared to large applications applied before emergence. Nitrogen applied through the hilling stage should be incorporated into the hill to maximize availability of the N to the potato root system.

Just as N fertilizer applied too early in the season can potentially lead to nitrate losses, so can N fertilizer applied too late in the season. Nitrogen applied beyond 10 weeks after emergence is rarely beneficial and can lead to nitrate accumulation in the soil at the end of the season.

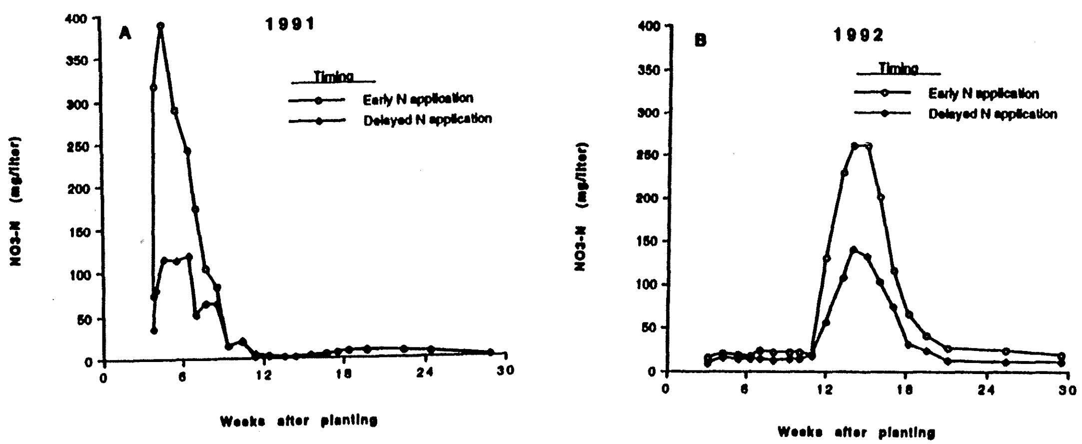


Figure 2. Effect of starter nitrogen application on nitrate concentrations in soil water at the 2.5 foot depth. A) Becker, 1991; B) Becker 1992. Early nitrogen application is 120 lbs N/A at planting, 60 lb N/A at emergence and 60 lb N/A at hilling. Delayed nitrogen application is 40 lb N/A at planting, 100 lb N/A at emergence and 100 lb N/A at hilling.

Table 3. Nitrogen starter effects on Russet Burbank potato yield, Becker - 1991.

Timing of N application			Tuber Distribution					
Planting	Emergence	Hilling	Knobs	<3 oz	3-7oz	7-14oz	>14oz	Total
lb N/A			cwt/A					
0	120	120	22	39	210	189	12	471
40	100	100	29	42	221	184	16	493
80	80	80	28	47	224	179	8	486
120	60	60	39	54	216	169	15	494

Table 4. Nitrogen starter effects on Russet Burbank potato yield, Becker - 1992.

Timing of N application			Tuber Distribution					
Planting	Emergence	Hilling	Knobs	<3 oz	3-7oz	7-14oz	>14oz	Total
lb N/A			cwt/A					
0	120	120	30	34	231	270	36	602
40	100	100	17	47	250	221	34	568
80	80	80	31	53	282	223	12	601
120	60	60	29	49	268	199	14	559

**** Use petiole analysis to aid in making post-hilling nitrogen applications**

Increases in N use efficiency have been shown when some of the N is injected into the irrigation water after hilling (fertigation). Because the root system of the potato is largely confined to the hill through the hilling stage, fertigation is only recommended after hilling. After hilling, potato roots do explore the furrow to some extent. Post-hilling N applications are most beneficial in years when excessive rainfall occurs before hilling (Table 5, Figure 3A). In dry years with minimal leaching, post-hilling applications show little if any advantages over applying N through the hilling stage from a production standpoint. However, leaching losses can still be reduced (Table 6, Figure 3B).

Table 5. Effect of post-hilling applications on Russet Burbank yield, Becker 1991.

Timing of N application				Tuber Distribution					
Planting	Emergence	Hilling	PH*	Knobs	<3 oz	3-7oz	7-14oz	>14oz	Total
lb N/A				cwt/A					
40	40	40	0	23	51	240	158	5	477
80	80	80	0	28	47	224	179	8	486
40	40	40	80**	36	42	221	200	13	512

*PH = post-hilling application
**two post-hilling applications of 40 lb N/A per application

Table 6. Effect of post-hilling applications on Russet Burbank yield, Becker - 1992.

Timing of N application				Tuber Distribution					
Planting	Emergence	Hilling	PH*	Knobs	<3 oz	3-7oz	7-14oz	>14oz	Total
lb N/A				cwt/A					
40	40	40	0	32	58	267	158	3	518
80	80	80	0	31	53	281	223	12	601
40	40	40	80**	29	58	246	195	14	541

*PH = post-hilling application
**two post-hilling applications of 40 lb N/A per application

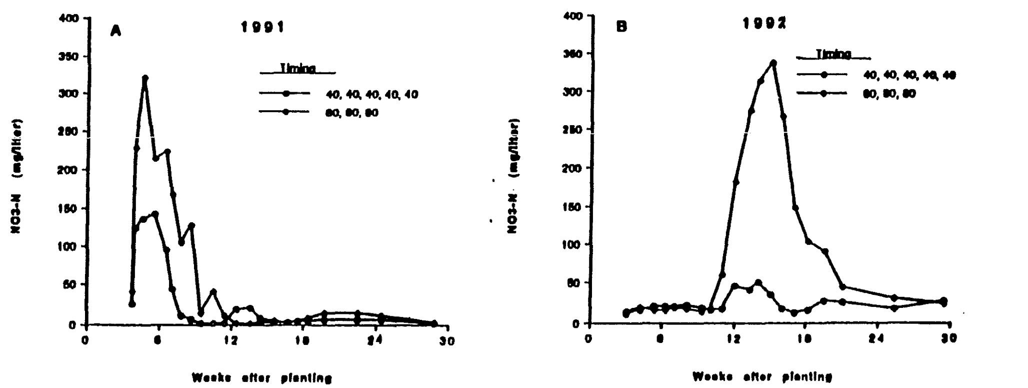


Figure 3. Effect of post-hilling N applications in combination with lower early season N applications on nitrate-N in the soil water at the 2.5 foot depth. A) Becker, 1991; B) Becker, 1992. Timing of N application: 80, 80, 80 refers to 80 lb N/A and planting, 80 lb N/A at emergence and 80 lb N/A at hilling (240 lb N/A total); 40, 40, 40, 40, 40 refers to 40 lb N/A and planting, 40 lb N/A at emergence 40 lb N/A at hilling, and two post hilling applications of 40 lb N/A (200 lb N/A total).

If post-hilling applications of N are used, then 2/3 to 3/4 of the recommended N fertilizer should be applied through the hilling stage. Timing of the remainder of the N applications should be based on petiole nitrate-N levels determined on either on dry weight or sap basis. Table 7 shows suggested sufficiency ranges for Russet Burbank potatoes through the growing season. Other potato varieties may slightly vary in sufficiency ranges. However, the ranges in Table 7 will still be a suitable starting point to adjust post-hilling N applications for other varieties as well. Typically if N is needed, 20 to 40 lb N/A can be injected per application.

Table 7. Petiole nitrate sufficiency levels for Russet Burbank potatoes on a dry weight and sap basis.

Time of Season/Stage of Growth	Sap NO_3-N	Dry wt. NO_3-N
	ppm	
Early Vegetative/tuberization (June 15 - June 30)	1300 - 1650	17,000 - 22,000
Mid Tuber growth/bulking (July 1 - July 15)	900 - 1200	11,000 - 15,000
Late Tuber bulking/maturation (July 15 - August 15)	550 - 700	6,000 - 8,000

One danger of relying on applying N through the irrigation system is if rainfall patterns during the time for fertigation are adequate or excessive. Applying N through the system in this case may potentially lead to an increase in nitrate leaching if high amounts of irrigation water are also applied. In situations where there is a demand for N, but rainfall has been adequate or excessive, low amounts (less than 0.3") of water should be applied with the N fertilizer. Another potential problem with delayed N application is if the potato crop dies back early due to insects or diseases. In this situation, N applied post-hilling may not be used as efficiently and post-hilling N applications may increase leaching losses. It is essential therefore, that an integrated cropping approach be taken to minimize nitrate leaching losses.

Selecting Appropriate Nitrogen Sources

**** Do not use fertilizers containing nitrate in the starter**

Each fertilizer N source used for potatoes has advantages and disadvantages, depending on how they are managed. However, because leaching often does occur in the spring, fertilizer sources containing nitrate (ie. UAN-28 and ammonium nitrate) at planting should be avoided. Ammonium sulfate, diammonium phosphate, monoammonium phosphate, or urea are the preferred N sources for starter fertilizer. Advantages of urea compared to ammonium nitrate are lower cost and delayed potential for leaching. Disadvantages of urea are that it is hygroscopic (attracts water), it must be incorporated after application or ammonia volatilization losses may occur, and its slow conversion to nitrate in cool seasons may reduce yields. Further research also needs to be conducted on the use of anhydrous ammonia for potato. Anhydrous ammonia may be beneficial in delaying the potential for leaching losses; however, positional availability of the N in relation to the hill may be a problem with sidedress applications. Preliminary research has shown that anhydrous ammonia application under the hill before planting can be an effective N source for potatoes.

Substantial reductions in nitrate leaching can occur if slow release sources of N are used. These slow release sources can also be applied earlier in the season without the fear of nitrate leaching losses. Further research with slow release sources needs to be conducted to evaluate effects on tuber quality. The main disadvantages of slow release N fertilizer are the higher cost compared to conventional quick release N fertilizers and delayed release to ammonium and nitrate when soil temperature are cool.

Manure can also be used as a slow release N source. Research has shown that in-season N losses can be reduced with manure, however, post-harvest N losses can be greater than conventional N fertilizer, especially when high rates of manure are applied. If manure is used, the rate applied should be based on estimated available N content. As with other slow release fertilizers, cool temperatures will delay the release of nitrate and ammonium.

Water Management Strategies

**** Follow proven water management strategies to provide effective irrigation and minimize leaching**

Water management has a profound effect on N movement. While leaching of nitrate due to heavy rains rainfall cannot be prevented, following the N management strategies discussed above will minimize the losses. However, over-irrigation even with optimum N rate applied and proper timing of N application, can cause substantial leaching losses. Therefore, effective water scheduling techniques based on soil moisture content and demand by the crop should be followed to prevent such losses. For more information on irrigation scheduling, refer to: Irrigation Water Management Considerations for Sandy Soils in Minnesota, AG-FO-3875.

Cover Crops Following Potatoes

**** Establish a cover crop following potatoes whenever possible**

For early harvested potatoes (July/August), any nitrate remaining in the soil is subject to leaching with rainfall. Establishing a cover crop such as winter rye will take up residual N to minimize this potential loss. An additional benefit of the cover crop is to reduce wind erosion. After the cover crop is killed or plowed under, N will be released from the vegetation the following spring. Cover crops can also be planted after potatoes harvested in September/October, although the purpose here is more for erosion control than to reduce N losses.

Suggested Best Management Practices for Irrigated Potatoes on Coarse-textured Soils

Best management strategies for irrigated potatoes need to be somewhat flexible because of differences due to soil type, unpredictable weather, and numerous potato cultivars grown. However, some general guidelines can be followed with the understanding that some modifications may be necessary and that fine-tuning BMPs for N is an ongoing process. Based on the research conducted with potatoes on sandy soils, the following best management options for N are suggested[1]:

[1]These suggestions are based on research with Russet Burbank. Response may vary with other varieties. More research needs to be conducted to fine-tune N timing for early harvested varieties.

Mid/late season varieties - Vines killed after mid-August

Option 1 - when fertigation is available

* apply 20 to 40 lb N/A in the starter (this amount should be included in the total N rate recommended)

* do not use fertilizer containing nitrate in the starter

* apply one third to one half of the recommended N at or around emergence, cultivate/incorporate the fertilizer into hill

* apply one third of the recommended N at final hilling, cultivate/incorporate the fertilizer into hill; on some heavier textured soils during rainy periods, it may not be possible to time this application properly due to row closure. In this situation, the N can be applied using fertigation

* base timing of subsequent N applications on petiole analysis, apply 10 to 40 lb N/A per application through the irrigation system

* establish a cover crop after harvest whenever possible

Option 2 - for mid/late season varieties when fertigation is not available:

* apply 20 to 40 lb N/A in the starter (this amount should be included in the total N rate recommended)

* do not use fertilizer containing nitrate in the starter

* apply one third to one half of the recommended N at or around emergence, cultivate/incorporate the fertilizer into hill

* apply the remainder of the recommended N rate at final hilling, cultivate/incorporate the fertilizer into hill

* establish a cover crop after harvest whenever possible

Option 1 has generally shown better N use efficiency, particularly during years when excessive rainfall has occurred before hilling. Remember that best management practices are based on the most current research available. As more information becomes available through research efforts, some modification of BMPs may be necessary.

Early season varieties, with or without fertigation - Vines killed in July/early August

* apply 20 to 40 lb N/A in the starter (this amount should be included in the total N rate recommended)

* do not use fertilizer containing nitrate in the starter

* apply one third to two thirds of the recommended N at or around emergence, cultivate/incorporate the fertilizer into hill

* apply one third to one half of the recommended N rate at final hilling, cultivate/incorporate the fertilizer into hill

* if fertigation is available: base timing of subsequent N application on petiole analysis, if needed, apply 10 to 30 lb N/A per application through the irrigation system

* establish a cover crop after harvest

Summary

Nitrogen is an essential plant nutrient that contributes greatly to the economic viability of irrigated potato production. Unfortunately, the nitrate form of N can leach into groundwater if N is not managed properly. Contamination of water resources by agricultural production systems will not be tolerated by the public and could lead to laws regulating the use of N fertilizers if this contamination is not minimized.

Research-based Best Management Practices (BMPs) have been developed specifically for irrigated potatoes and integrated into the BMPs that were developed previously for other agronomic crops. Various strategies are provided that take into account N rate, timing of application, method of application, N source, and varieties/harvest date. The main objectives of these BMPs are to maintain profitability and minimize nitrate leaching. By following these recommendations, the threat of fertilizer regulations can be avoided and a more profitable and better community can be attained.

Appendix A

Nitrogen Recommendations for irrigated potato production

Yield Goal*	Previous Crop			
	alfalfa (good stand)	soybeans field peas	any crop in group 1[*]	any crop in group 2[*]
cwt/A	N to apply (lb/A)			
less than 200	15	55	35	75
200 - 249	40	80	60	100
250 - 299	65	105	85	125
300 - 349	90	130	110	150
350 - 399	115	155	135	175
400 - 449	140	180	160	200
450 - 499	165	205	185	225
500 or more	190	230	210	250

*Yield in this table refers to total yield not marketable yield

Crops in Group 1	Crops in group 2		
alfalfa[1] (poor stand)	barley	grass hay	sorghum-sudan
alsike clover	buckwheat	grass pasture	sugarbeets
birdsfoot trefoil	canola	mullet	sunflowers
grass-legume hay	corn	mustard	sweet corn
grass-legume pasture	edible beans	oats	triticale
red clover	flax	potatoes	wheat
fallow	rye	vegetables	

[1]Poor stand is less than 4 crowns per sq. ft.

Minnesota Department of Agriculture

February 13, 1995 (612) 297-7178

Mr. James Japs
Water Appropriations
Department of Natural Resources
300 DNR Building
St. Paul, MN 55107

FEB 15 1995

RE: Draft Potato BMPs / Issue for Irrigation Permit #91-

Dear Jim,

Enclosed are the proposed *Best Management Practices for Nitrogen Use: Irrigated Potatoes*. Dr. Carl Rosen, Soil Scientist at the Department of Soil Science-University of Minnesota, is the author and principal researcher. Dr. Rosen has requested and received input from his colleagues and Bruce Montgomery (MDA) in previous draft versions. After recent consultation with Mr. Paul Gray, representing Area II Potato Growers, we feel that the BMPs are ready for the next step in the review process by distributing to growers for their comments. The MDA will distribute the proposed BMPs at the 1995 Area II Potato Workshop on March 9, 1995 in Monticello. I have attached an agenda.

Dr. Rosen has done an outstanding job in the development of these BMPs. Dr. Rosen's work, largely funded through LCMR, strongly indicates that timing of nitrogen is critical in reducing N leaching losses while maintaining yields. The incorporation of "in-field" petiole testing will aid producers who fertigate.

While these BMPs are still in draft form, they will serve as the foundation for the BMPs the MDA intends to adopt to reduce the impacts of potato production on Minnesota's ground water. Please consider incorporating the attached management strategies as part of the conditional use permit for irrigation permit (91-) for the 1995 cropping season.

RECEIVED
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DNR WATERS-R3
LITTLE FALLS

C.1-37

The Minnesota Department of Agriculture will keep you updated with the process of the adoption of the potato BMPs. I anticipate getting the revised BMPs into the State Register this spring for formal public response. In accordance with the MDA's policy and statute, we will be discussing these BMPs with growers prior to the formal comment period. Unless there is significant new information and/or research provided, the **final** BMPs should be published in the State Register in early summer. We will work with the growers and related industries to begin the promotion of the BMPs in 1995 and, more significantly, in 1996.

Sincerely,

Greg Buzicky
Director, Agronomy Services Division
Minnesota Department of Agriculture

CC:
Farm Company
Paul Gray, Area II Potato Growers
Dr. Carl Rosen, University of Minnesota
Bruce Montgomery, MDA

Enclosures

STATE OF MINNESOTA
DEPARTMENT OF NATURAL RESOURCES

Division of Waters, Route 4, Box 19A, Little Falls, MN 56345
PHONE NO. 612/632-2430 FILE NO.

March 30, 1995

Ms. Isabel Jenson, District Manager
Benton SWCD
152 Norman Avenue South
Foley, MN 56329

PERMIT 91- , AGRICULTURAL IRRIGATION, ,
BENTON COUNTY

Dear Ms. Jensen:

The Department of Natural Resources (DNR) has received a request to grow potato crop on irrigated fields authorized under Permit 91- . As you may recall, the District recommended denial of this permit based on the ground water quality problems (high nitrate levels) associated with agricultural irrigation. The DNR eventually issued a temporary permit authorizing irrigation of crops that utilize the Minnesota Department of Agriculture (DOA) approved Best Management Practices (BMP's) for nitrate reduction.

The permit was converted on February 14, 1994 from a temporary status to irrigation on a seasonal basis each year. A condition was attached to the permit that prohibited growing potato crop until BMP's were developed by the DOA to address the water quality concerns.

Enclosed are proposed *Best Management Practices for Nitrogen Use: Irrigated Potatoes*, drafted by the DOA. The Department requests that the District review the enclosed information and express any comments or concerns they may have.

If you have any questions, please don't hesitate to contact me.

Sincerely,

Timothy L. Crocker
Area Hydrologist

Enclosures

c: Dave Hills, Regional Hydrologist
Jim Japs, Water Use and Appropriations Hydrologist
Greg Buzicky, Director, Agronomy Services Division, MN-DOA
Mr. John Wojtanowicz, 3000, 145th St. N.W., Rice, MN 56367

Minnesota Department of Agriculture

May 26, 1995 (612)296-5639

Mr.
Route 1,
Royalton, Minnesota 56373

REGARDING: Request for Review and Comment on the Revised Version of *"Best Management Practices for Nitrogen Use: IRRIGATED POTATOES"*

Dear Mr. :

Over the past four years, the State of Minnesota has officially adopted voluntary Best Management Practices (BMPs) for managing nitrogen resources for our agricultural and urban communities. The final product is a series of common sense practices that have evolved as a result of years of research from the University of Minnesota and surrounding land grant universities. Farmers, educators, leaders of agriculture, scientists - as well as environmentalists - have all reached consensus that these practices are a reasonable approach in maintaining farm profitability while minimizing the potential water quality impacts from agriculture.

As a result of aggressive research programs conducted by the Department of Soil, Water & Climate of the University of Minnesota, a draft series of management practices have been developed. This information was presented at the Area II Potato Growers annual meeting held on March 9, 1995. Since that time, representatives from Area II and Dr. Carl Rosen have incorporated a number of changes as a direct result of the discussion held at that meeting.

The MDA would like to finalize these practices by the end of the summer. After consultation with Paul Gray and Curt Klint, representing the Area II Potato Growers, we felt the feasible method for hearing your comments was through a direct mailout. Please *carefully review the enclosed draft document* and place any comments you may have directly on the copy itself. Keep in mind that the BMPs can undergo various modifications in the future as we incorporate *new* research findings. I would appreciate receiving your comments on or before June 30, 1995. A self-addressed, stamped envelop is enclosed for your convenience.

On behalf of the Minnesota Department of Agriculture and the University of Minnesota Extension Service, I would like to thank all the potato growers and the related industry for your cooperation. I look forward to working with you and reviewing your comments.

Sincerely,

Greg Buzicky, Director
Agronomy Services Division

GCB:clj

Enclosures

CC: Bruce Montgomery
Dr. Carl Rosen

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Nitrogen Source Effects on Irrigated Corn/Potato Yields and Nitrate Leaching, 1993[1]

J.T. Waddell, J.F. Moncrief,
C.J. Rosen, S.C. Gupta and M.J. Weins[2]

Abstract

Plots were established at Staples, MN with the following treatments: Anhydrous ammonia with and without nitrification inhibitor, turkey manure, urea-ammonium nitrate, granular urea and a control. Each treatment (except the control) had fertilizer applied at approximately 200 pounds N per acre. No differences in yield or moisture content occurred in the corn grain supplied with different N sources, however a significant increase in grain yield was observed versus the control. Stover yields were found to be non-significant. Potato tubers and vines did respond to the different N sources. Anhydrous ammonia and turkey manure applied preplant and subject to 10 inches of rainfall in May still resulted in similar marketable and total potato yields to other N sources that were applied in split applications in June and July. There was also a significant potato response to nitrification inhibition. A comparison of vine dry matter yield shows that using urea as an N source enhances vine growth. Nitrogen collected in suction cups was lower for corn than potato.

Introduction

Crop production on the sandy soils in Minnesota has been advanced by the introduction of irrigation systems (Wright and Bergsrud, 1991). Wright and Bergsrud (1991) developed an irrigation schedule termed 'the Checkbook Method' which predicts daily water use for several different crops. It has been shown by Dylla et. al. (1980) that these tables to predict water use are comparable to estimates obtained by more precise methods. While the checkbook method may be a valuable tool for predicting irrigation scheduling, the variability of climate from year to year plays a major role in assessing the risks of loosing nitrogen to sub-surface water reservoirs. It has been shown that varying the source of nitrogen (either Urea or Turkey manure) in corn cropping systems may have an effect on yields and contribute to contamination of groundwater (Nathan et. al., 1992 and Sexton 1993). Nitrogen source studies on potato yield in Minnesota are infrequent.

It was the purpose of this study to discern the effects of nitrogen source on corn/potato yields and to qualitatively describe N movement below the root zone.

Materials and Methods

The test plots were located on a Verndale sandy loam. The site had a maximum slope of 2% with little or no runoff. Soils of the area are unique. An illuvial soil horizon of limiting hydraulic conductivity (0.54 in h^{-1}) exists with a clear upper boundary at approximately 10 inches and a gradual lower boundary at 16 inches below the surface (Sexton, 1993). Visual observations of the soil showed a limited number of preferential flow paths (macropores) due primarily to ant burrows. Earthworms are less common on soils of such a sandy nature.

Individual plots were 20 x 40 square feet. Corn (Pioneer 3921) was planted on 5 May in 30 inch rows at a rate of approximately 32,000 seeds per acre. A blended starter fertilizer was applied at rates of 17 N, 6 P_2O_5, 34 K_2O, 11 S (pounds per acre). On 6 May, the herbicides Bladex (cyanozine) and Dual (metalachlor) were applied at rates of 2.5 pounds and 2 pints per acre, respectively. No insect of fungus control procedures were needed in the corn. Weed control was good with a few weeds (quackgrass, lambsquarter and nightshade). Some eyespot was observed in the corn plots.

Potato (Russet Burbank) was planted on 27 April in 36 inch rows with a density of 43560 seed pieces per acre along with 30 pounds N per acre. On 5 May, additional blended starter fertilizer (15-5-30-10) was applied at a rate equivalent to 114 pounds per acre. Pre-plant and post-harvest knock down herbicide Diaquat was applied at rates of 1.5 pints per acre, otherwise weeds were controlled during the growing season by cultivation on 25 June. Furadan was applied on 27 July after noticing Colorado Potato Beetle infestation. Fungicide (Bravo) was applied on 23 June, 2 and 9 July, and 13 August (with Ridomil) at rates of 1.5 pints per acre. Some Early Blight was detected during the growing season.

Nitrogen (approximately 170 pounds per acre) was applied to all plots totalling 200 pounds per acre. Each plot was a completely random design with four replications. This conservative rate for high yields was used in order to discern differences if any in the uptake and loss of nitrogen. Table 1 shows the application rates and schedules of the various treatments. Anhydrous ammonia was placed below the row for potato and between the row for corn sidedress on 30 June.

Irrigation scheduling was based on the Checkbook Method (Wright and Bergsrud, 1991), with attempts to apply 0.75 inches (Figure 1). During the

[1] *Support for this project was provided by the Legislative Commission on Minnesota Resources. Their support is greatly appreciated.*

[2] *J.T. Waddell, Graduate Research Assistant, J.F. Moncrief and C.J. Rosen, Extension Specialists, S.C. Gupta, Professors of Soil Sci., Dept. Soil Sci., Univ. Minn, St. Paul, MN. M.J. Wiens is the Univ. Minn. Senior Plot Coordinator, Staples Irrigation Center, Staples, MN.*

corn stages from planting to 12 leaf, irrigation was applied at a deficit of 60% of the available water (1.42 inches); from 12 leaf to first dent, the irrigation trigger was 0.95 inches (40%); and from first dent to maturity, irrigation was initiated at 66% (1.6 inches) depletion. For potatoes, an irrigation deficit of 50% was used from planting to tuberization and from tuberization to maturity a 40% deficit was used. Rainfall events which exceeded half of field capacity were followed by two days of cumulative soil water deficits at zero. Whenever the water deficit by the Checkbook Method was less then 10 centibars of tension, suction was applied to suction cup samplers. Also, suction was applied to samplers before irrigation events or when the chance of precipitation was 50% or greater.

Suction samplers were made from high flow (1 bar) porous ceramic cups (2 inch diameter) were glued to poly vinyl chloride (PVC) pipe. Access tubes were inserted through a rubber stopper from which suction was used for collection of soil water percolate. Suction samplers were installed in plots amended with Urea and turkey manure along with the control plot. Suction samplers were installed at the 24 inch depth. Samples collected were quickly frozen and taken to the analytical lab where nitrate and ammonia concentrations were measured.

Corn was harvested by hand on 21 October. Stover and grain moisture content, yield and N uptake were determined. Potatoes were harvested on 16 September with biomass, N accumulation and quality parameters determined.

Results and Discussion

From figure 1, it is evident that rainfall was not limiting during the growing period except for a few instances when irrigation was used. Ample or excess rainfall occurred in all months except June and July which were close to average values determined at the Irrigation Center. Mean temperatures were below normal for the growing season. For this reason, corn yields may have been depressed.

Corn

Table 2 shows the parameters measured for corn. No differences were seen in stover accumulation, likewise for grain yield (except in the case of grain, the control yielded significantly less). The lack of significant differences may be attributed to large variabilities between replications. Average grain yield over all treatments (except control) was 110 bushels per acre and for stover 1330 pounds per acre. Because of the wet and cold growing season, drying time was reduced as seen by moisture content in the grain (> 30%) and stover (50 to 70% water). Again, no differences were observed in grain moisture content and only slight differences in stover water content, due to high variability between replications.

Nitrogen uptake in corn grain and stover is also shown in table 2. Plots with urea as the nitrogen source had the highest N uptake, although not significantly different then the anhydrous ammonia (with and without N-serve) or the urea ammonium nitrate (28%) sources. Nitrogen uptake in the urea plot was significantly greater than the turkey manure treatment. Figure 2 shows total nitrogen concentrations in soil water collected with suction samplers. From the figure, it can be seen that the N content moving out of the root zone increased steadily over time until mid August after which it dropped off. Increased uptake of nitrogen during the middle of the growing season is evident from the drop in the curve in the check plots, after which the concentration of N in the water increased probably due to mineralization of organic matter.

The first week in July shows the greatest moisture excess of approximately 1.5 inches in a week. Nitrogen lost in the turkey manure treatment increased sharply probably as a result of high mineralization rates which increased the potential for leaching.

Potato

Table 3 shows the response of potato tubers to the different nitrogen sources. Marketable tuber yield was highest with the anhydrous application with N-serve, however this yield (338 cwt/ac) was not significantly different than the urea or turkey manure sources. The urea and AA (with N-serve) did yield significantly higher than the AA (without) and the 28% treatments. Besides marketable tubers, total tubers harvested followed a similar trend. Vine yield, which may not be economically important to the farmer, is important in accumulating nitrogen and perhaps reducing nitrate concentrations in subsurface water reservoirs. Table 3 shows that N accumulation in the vine was highest for the urea treatment. However, vine yields and N concentrations play only a minor role in the N budget. Nitrogen uptake in tubers was highest for AA with and without N-serve and urea treatments. Turkey manure amended to plots was not as efficient a source in that N uptake was less. As a result of tuber yield in turkey manure amended treatments not being significantly less than other treatments, luxury consumption of nitrogen was not a factor. Instead, as the growing season progressed the organic fraction of N in the turkey manure may have been made more available. Figure 3 shows nitrogen concentrations in soil water peaked for the manure treatments during the final stage of the growing season. A possible explanation would be that as mineralization increased (as can also be seen by the upward trend in the control treatment) plant requirements also increased. As the plants matured, the manure was still mineralized and as a result became susceptible to leaching. Figure 3 also shows the N content in soil water under plots amended with urea. The very high peak in late June after the second urea application may not actually be potentially leached. The samples collected from this treatment at this time contained as much as half the total in the form of ammonium. The lower leaching potential of NH_4^+ leads to questions of its arrival at the 2 foot depth. One explanation is that as a result of significant precipitation after urea application, the urea was solubilized and moved to the lower depth where it hydrolyzed and transformed into nitrate (by nitrification bacteria) and ammonium (hydrolysis product).

Summary

Rainfall during months from May through September totalled over 25 inches (25 year mean rainfall = 16.7 inches), resulting in above average leaching conditions. Grain and stover yields did not differ significantly compared to different N sources at approximately equivalent rates. The response of greatest marketable tuber yield with application of Turkey manure, urea and anhydrous ammonia occurred. However, these results only apply in the case of above average rainfall. Nitrogen budgets following harvest may be incomplete. Residual nitrogen in soil was not measured after harvest. In order to determine whether different sources of N plays a role in yields and losses, further study must occur. This study will be continued next year.

References

Dylla, S.A., D.R. Timmons, and H. Shull. 1980. Estimating water used by irrigated corn in West Central Minnesota. Soil Sci. Soc. Am. J. 44:823-827.

Nathan, J.V., G.L. Malzer, and J.L. Anderson. 1992. Impact of turkey manure application on corn production and potential water quality concerns on Estherville Sandy Loam. MN Ag. Exp. St., Misc. Pub 75-1992. University of Minnesota.

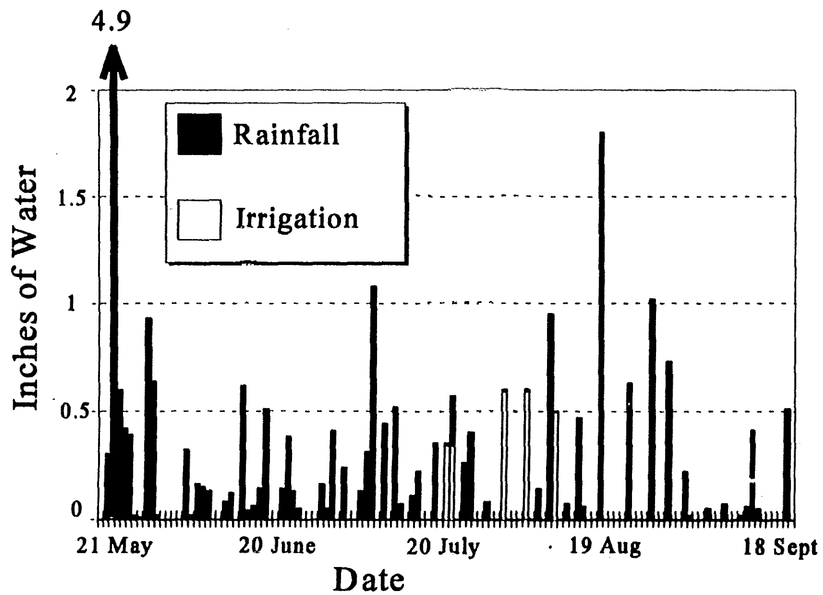
Sexton, B.T. 1993. Influence of nitrogen and irrigation management on corn and potato response and nitrate leaching. Masters of Science Thesis, University of Minnesota Soil Science Department.

Wright, J., and F. Bergsrud. 1991. Irrigation Scheduling: the Checkbook Method. MN Ext. Ser. AG-FO-1322-C. University of Minnesota.

Table 1. Nitrogen sources, application rates and dates.

Treatment	Potato		Corn	
	Rate	Date	Rate	Date
Anhydrous Ammonia with N-serve	197 (165)† lbs/ac	22 April	197 (165) lbs/ac	30 June
Anhydrous Ammonia	197 (165) lbs/ac	22 April	197 (165) lbs/ac	30 June
Urea	364 (85) lbs/ac	1 and 25 June	364 (85) lbs/ac	1 and 25 June
Urea Ammonium Nitrate (28%)	300 (85) gal/ac	1 and 25 June	300 (85) gal/ac	1 and 25 June
Turkey Manure	6.8 (211) tons/ac	21 April	6.8 (211) tons/ac	21 April

† Values in parenthesis represent the calculated applied N (pounds per acre) for each source. Note that an additional 47 pounds N per acre was applied to potato and 17 pounds N per acre of corn in starter application.



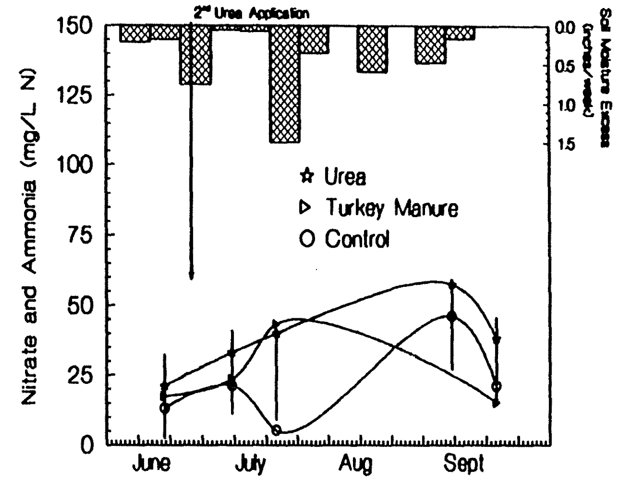


Figure 2. Soil water nitrate concentrations under corn from suction cup samplers (24 inch depth) along with soil moisture excess calculated by the checkbook method.

Table 2. Response of corn to different nitrogen sources.

Nitrogen Source	Grain Yield	Grain Moisture	Stover Yield	Stover Moisture	Nitrogen Uptake		
					Grain	Stover	Total
	bu/ac	%	lbs/ac	%	------------lbs/ac------------		
Anhydrous Ammonia with N serve	106.6a	32.1a	1241a	64.6ab	75.7ab	11.1abc	86.8 b
Anhydrous Ammonia without N serve	107.0a	32.3a	2045a	50.4 b	75.0ab	17.4a	92.4ab
Urea	113.0a	32.6a	1073a	58.0ab	84.7a	17.1ab	101.8a
28%	107.7a	32.3a	1094a	77.7a	74.2ab	9.2abc	83.4 b
Turkey Manure	116.9a	31.7a	1314a	73.9a	73.4 b	8.8 bc	82.2 b
Control	70.1 b	33.4a	1220a	64.4ab	39.6 c	6.6 c	46.2 c

Means within a column followed by the same letter are not significantly different using Duncan's Multiple Range Test ($\alpha = 0.1$)

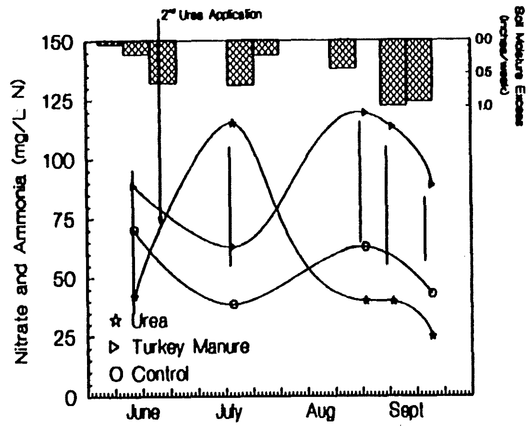


Figure 3. Soil water nitrate concentrations under potato along with soil moisture excess (calculated by checkbook method) and error represent standard errors.

Table 4. Some quality parameters and Nitrogen uptake values along with moisture content of tuber data.

Nitrogen Source	Specific Gravity	Hollow Heart	Tuber N uptake	Tuber Water Content	Vine N Uptake	Vine Water Content
	g cm^{-3}	%	lbs / ac	%	lbs / ac	%
Anhydrous Ammonia with N Serve	1.096a	8.0 b	121a	75.8abc	18.6 bc	86.7a
Anhydrous Ammonia without N serve	1.095a	12.0ab	116ab	75.3 c	20.0 b	85.5a
Urea	1.094a	9.0 b	118ab	76.6a	32.9a	86.6a
28%	1.095a	10.0 b	106 bc	75.6 bc	20.2 b	87.5a
Turkey Manure	1.096a	9.0 b	99 c	76.3a	9.44 cd	87.8a
Control	1.095a	18.0a	52 d	75.6 bc	2.76 d	67.5 b

Means within a column followed by the same letter are not significantly different using Duncan's Multiple Range Test (α=0.1).

Table 3. Response of potato tubers to different nitrogen sources totalling to 210 (± 5) lbs/ac applied N.

Nitrogen Source	Culls	Ones	Twos	Jumbo	Knobs	Market	Total	Vine Yield
		----------cwt/ac----------						lbs/ac
Anhydrous Ammonia with N serve	23.0ab	139.9a	198.7a	9.1ab	11.6b	338a	382ab	1093b
Anhydrous Ammonia without N serve	21.6ab	120.2a	176.1a	15.4a	11.5b	296b	344ab	1070b
Urea	19.0b	161.4a	172.9a	10.0ab	23.9a	334a	387a	1999a
28%	18.6b	129.9a	160.8a	17.9a	14.5ab	290b	341b	1218b
Turkey Manure	24.5ab	122.8a	191.3a	6.7ab	24.3a	314ab	369ab	965b
Control	28.8a	32.9b	162.7a	0.6b	5.4b	195c	230c	318c

Means within a column followed by the same letter are not significantly different using Duncan's Multiple Range Test (α=0.1).

Nitrogen Source Effects on Corn/Potato Yields and Nitrate Leaching, 1994[1]

J.T. Waddell, J.F. Moncrief, C.J. Rosen, S.C. Gupta, M.J. Weins, B. Sheets, and B.J. Johnson[2]

Abstract

Plots were established at Staples, MN to evaluate the following nitrogen sources: anhydrous ammonia, turkey manure, urea-ammonium nitrate (28%), granular urea and a control. An attempt was made to give each treatment (except the control) approximately 200 lbs N per acre, however the turkey manure treatment received 250 lbs N per acre. No differences in yield or moisture content was observed in corn grain supplied with different N sources. Potato tubers and vines did respond to different N sources. Measurement of N lost below the root zone indicates that turkey manure increased losses, however more N was applied in this treatment. Water use by corn was slightly lower during the early part of the growing season when percolation losses were highest. Except in the case of turkey manure, there was more nitrate leaching under corn.

Introduction

Crop production on sandy soils in Minnesota has been improved by the introduction of irrigation systems. Wright and Bergsrud (1991) produced an irrigation schedule termed 'the Checkbook Method' which predicts daily water use for several different crops in Minnesota using overhead sprinkler irrigation. It has been shown by Dylla et. Al. (1980) that these tables to predict water use are comparable to estimates obtained by more precise methods. While the checkbook method may be a valuable tool for predicting irrigation scheduling, the variability of climate from year to year plays a major role in assessing the risks of loosing nitrogen to sub-surface reservoirs.

It has been shown that varying the nitrogen source can have an effect on yields and contribute to contamination of groundwater (Nathan et al., 1992 and Sexton, 1993). Typically, growers in the central sands region of Minnesota have used urea as a nitrogen source. This source of nitrogen is readily available to plants once it is hydrolyzed. However, it may be rapidly leached into subsurface reservoirs during heavy rainfall events. Another nitrogen source is turkey manure. Minnesota is the second leading producer of turkeys in the United States. As a result, turkey manure is abundant and its disposal is of growing concern. Turkey manure is unique as a nitrogen source since its components include primarily ammonium and organic nitrogen compounds. The ammonium portion is readily available to plants while the organic N portion is more slowly made available for uptake throughout the growing season and into the next.

It was the purpose of this study to discern the effect of nitrogen sources on corn/potato yields. Another goal of this project is to quantitatively describe N movement below the root zone.

Materials and Methods

The test plots were located on a Verndale sandy loam soil. The site had a maximum slope of 2% with little or no runoff. Soils of the area are unique. An illuvial soil horizon of limiting hydraulic conductivity (0.54 in h^{-1}) exists with a clear upper boundary at approximately 10 inches and a gradual lower boundary at 16 inches below the surface (Sexton, 1993). Visual observations of the soil showed a limited number of preferential flow paths (macropores) due primarily to ant burrows. Earthworms are less common on soils of such a sandy nature.

Individual plots were 20 x 40 square feet. Corn (Pioneer 3921) was planted on 5 May in 30 inch rows at a rate of approximately 32,000 seeds per acre. A blended starter fertilizer was applied at rates of 30 N, 128 P_2O_5, 68 K_2O, 11 S (pounds per acre). On 6 May, the herbicides Bladex (cyanozine) and Dual (metalachlor) were applied at rates of 2.5 pounds and 2 pints per acre, respectively. No insect of fungus control procedures were needed in the corn. Weed control was good with a few weeds (quackgrass, lambsquarter and nightshade).

Potato (Russet Burbank) was planted on 26 April in 36 inch rows with a density of 17,424 seed pieces per acre. A blended starter fertilizer (7.5-32-17-3.1) was applied at a rate equivalent to 400 pounds per acre. Pre-plant and post-harvest knock down herbicide Diaquat was applied at rates of 1.5 pints per acre, otherwise weeds were controlled during the growing season by cultivation on 14 June. Furadan was applied on 27 July after noticing Colorado Potato Beetle infestation. Fungicide (Bravo) was applied weekly at rates of 1.5 pints per acre. Some Early Blight was detected

[1] *Support for this project was provided by the Legislative Commission on Minnesota Resources. Their support is greatly appreciated.*

[2] *J.T. Waddell, Graduate Research Assistant, J.F. Moncrief and C.J. Rosen, Extension Specialists, S.C. Gupta, Professor of Soil, Water, and Climate, University of Minnesota, St. Paul, Minnesota. M.J. Weins is the University of Minnesota Senior Plot Coordinator, Central Minnesota Economic Development, Research and Education Center, Staples, MN. B. Sheets and B.J. Johnson, Magnificent Technicians, CMEDREC and U of M, respectively.*

during the growing season.

Nitrogen (approximately 170 pounds per acre) was applied preplant (anhydrous ammonia) or in two applications (urea and 28%) to both corn and potato plots totaling 200 pounds per acre except for the turkey manure treatment (Table 1). The plots were structured as a completely random design with four replications. This conservative rate of 200 lbs per acre was used in order to discern differences if any in the uptake and loss of nitrogen. Table 1 shows the application rates and schedules of the various treatments. Anhydrous ammonia was placed pre-plant below the row for potato and between the row for corn sidedress on 10 June.

Irrigation scheduling was based on the Checkbook Method (Wright and Bergsrud, 1991), with attempts to apply 0.75 inches (Figure 1). During the corn stages from planting to 12 leaf, irrigation was applied at a deficit of 60% of the available water (1.42 inches); from 12 leaf to first dent, the irrigation trigger was 0.95 inches (40%); and from first dent to maturity, irrigation was initiated at 66% (1.6 inches) depletion. For potatoes, an irrigation deficit of 50% was used from planting to tuberization and from tuberization to maturity a 40% deficit was used. Rainfall events which exceeded half of field capacity were followed by two days of cumulative soil water deficits at zero. Whenever the water deficit by the Checkbook Method became close to exceeding the water holding capacity, suction was applied to suction cup samplers. Also, suction was applied to samplers before irrigation events or when the chance of precipitation was 50% or greater.

Suction samplers were made from high flow (1 bar) porous ceramic cups (2 inch diameter) glued to poly vinyl chloride (PVC) pipe. Access tubes were inserted through a rubber stopper from which suction was used for collection of soil water percolate. Suction samplers were installed in plots amended with urea and turkey manure along with control plots. Suction samplers were installed at the 24 inch depth. Samples collected were quickly frozen and taken to the analytical lab where nitrate and ammonia concentrations were measured.

Corn was harvested by hand on 21 September. Stover and grain moisture content, yield and nitrogen content were determined. Potatoes were harvested on 16 September with biomass, N accumulation and quality parameters determined.

Results and Discussion

Rainfall and irrigation events are shown in Figure 1. Percolation values were calculated from a water budget using the equation:

$$\textit{Percolation} = \textit{Rain} + \textit{Irrigation} - \textit{WaterUse} - \Delta \textit{Storage}$$

It is obvious that leaching losses below the root zone were prevalent early in the growing season just after fertilizer side dressing. Percolation losses in figure 1 were averaged from water use both for corn and potato. Water use (estimated from the Checkbook Method) for potato was greater than that of corn until day 200 (19 July) when uses were equal. After this time, corn water use was slightly greater than potato. During the latter portion of the growing season the center pivot irrigation device malfunctioned and corn may have been slightly stressed.

Corn

Corn yields are shown in table 2. All treatments yielded more grain than the control. The turkey manure treatment yielded highest with 232 bushels per acre. An explanation causing significantly higher yields with turkey manure include higher N fertilizer rates. Preliminary analysis of turkey manure indicated lower estimated available N than when we applied the manure to the plots. Other sources of nitrogen showed no significant difference in yield of corn grain (187 bu/ac). No difference in moisture content of the grain was observed. Stover yields for the 1994 growing season showed similar trends as did the grain. Turkey manure yielded the most stover producing over 2 tons per acre. The urea and turkey manure treatment yields were significantly higher than the control. Nitrogen uptake in corn grain had the exact trend as did the grain yield (table 2). Corn plots amended with turkey manure showed the highest N uptake, followed by plots ammended with the three chemical N forms, all yielding higher than the control. Similarly, nitrogen in stover was significantly higher in the turkey manure amended plots. Interestingly, the uptake of nitrogen from stover in the 28% plots was not significantly higher than the control. One component of the nitrogen budget (N lost below the root zone) is shown in figure 2. Nitrogen leached was calculated by multiplying nitrogen concentrations obtained from suction cup samplers by the volume of water estimated from figure 1. Because only three treatments (turkey manure, urea, and control) were instrumented, some questions arise from leaching of the other sources and cannot be answered without further study. Because of the lack of leaching events occurring this year, not much N was leached in either treatments compared to the control. Still, the general trend of N leaching follows closely the amount of nitrogen applied with the turkey manure treatment being highest followed by urea as a nitrogen source and finally the control.

Potato

Potato yields are shown in table 3. Marketable tuber yields for the different nitrogen treatments were not significantly different while all were higher than the control. Total tuber yields were highest for the turkey manure, anhydrous ammonia and urea treatments leading to a conclusion that the extra N applied to potatos was not effective in increasing tuber yield. However, increased vine growth occurred with higher N rates supplied from turkey manure. Another interesting occurrence is the abundant quantity of knobs (misshappen tubers) for plots amended with urea. It is unknown why this occurred, except that this particular treatment had the highest standard deviation.

The quality of tubers was influenced by the different nitrogen sources for this particular growing season (table 4). Plots with turkey manure applied as the nitrogen source had the lowest density relative to water. This value was significantly lower than the other chemical N sources but not different than the control. The incidence of hollow heart determined from 25 tubers showed that the fewest occurred in nitrogen treatments other than anhydrous ammonia amended plots. While potato scab was qualitatively measured, no significant differences occurred in the treatments with maximum percentages less than 8%(data not shown).

Nitrogen uptake and tuber water contents are also shown in table 4. While water contents in the tubers were not significantly different, vine water contents were different. It was evident at the time of harvest that vines in plots with turkey manure were actively growing, while the other treatments (especially the control) had begun to senesce. Nitrogen used by tubers indicates that all N treatments were similar and greater then the control. Vine uptake of nitrogen was highest in the turkey manure plots possibly as a result of luxury consumption. The chemical N sources all had similar uptake patterns at harvest and the control was least. Because of the increased uptake of nitrogen by the vines, total N uptake was greatest for the turkey manure treatment followed by the other N ammended treatments, all of which were significantly higher than the control. Nitrogen leached below the potato root zone was determined by multiplying the concentration of nitrogen from suction cup samplers by the percolation values obtained from the water budget. A plot of N leached throughout the growing season is shown in figure 3. The data indicates that highest leaching of N occurred under plots with turkey manure. This was probably due to the higher N rate as stated in the discussion section for corn.

Conclusions

The 1994 growing season was excellent with respect to potato/corn yield and nitrogen losses during the growing season. For corn, the amount of N (as seen in grain yields in table 2) may have been limiting as increased yields occurred in the turkey manure plots with 55 lbs/ac more N applied. The same is not true for potato yield since the increased N rates from turkey manure did not significantly increase tuber yield. Generalizations on the effectiveness or efficiency of turkey manure on yields and N leaching cannot be made since the N rate was much higher. Nitrogen forms other than turkey manure produced similar yields in corn grain and marketable tuber yield. However, as costs of nitrogen fertilizers are almost guaranteed to rise, the use of turkey manure may increase as a cheap effective source on nitrogen.

References

Dylla, S.A., D.R. Timmons, and H. Shull. 1980. Estimating water used by irrigated corn in West Central Minnesota. Soil Sci. Soc. Am. J. 44:823-827.

Nathan, J.V., G.L. Malzer, and J.L. Anderson. 1992. Impact of turkey manure application on corn production and potential water quality concerns on Estherville Sandy Loam. MN Ag. Exp. St., Misc. Pub 75-1992. University of Minnesota.

Sexton, B.T. 1993. Influence of nitrogen and irrigation management on corn and potato response and nitrate leaching. Masters of Science Thesis, University of Minnesota Soil Science Department.

Wright, J., and F. Bergsrud. 1991. Irrigation Scheduling: the Checkbook Method. MN Ext. Ser. AG-FO-1322-C. University of Minnesota.

Table 1. Nitrogen sources, application rates and dates.

Treatment	Potato Rate	Potato Date	Potato Total§	Corn Rate	Corn Date	Corn Total
Anhydrous Ammonia	206 (170)† lbs/ac	21 April	200 lbs/ac	206 (170) lbs/ac	10 June	200 lbs/ac
Urea	364 (85) lbs/ac	3 & 14 June	200 lbs/ac	364 (85) lbs/ac	3 & 14 June	200 lbs/ac
Urea Ammonium Nitrate (28%)	300 (85) gal/ac	7 & 24 June	200 lbs/ac	300 (85) gal/ac	7 & 24 June	200 lbs/ac
Turkey Manure	9.0 (245)‡ tons/ac	23 April	245 lbs/ac	9.2 (244) tons/ac	23 April	255 lbs/ac

§ Represents total nitrogen applied to individual plots including starter fertilizer.
† Values in parenthesis represent the calculated applied N (pounds per acre) for each source. Note that an additional 30 pounds N per acre was applied to potato and corn in starter application.
‡ Estimated available nitrogen = 100% mineral N(16.5 lbs/ton) + 30% organic N (34.9 lbs/ton). Moisture content was 32.9% by weight.

Table 2. Response of corn to different nitrogen sources.

N-source	Grain Yield	Grain Moisture	Stover Yield	Stover Moisture	------------	N-uptake	------------
					Grain	Stover	Total
	bu/acre	%	lb/acre	%	lb/acre	lb/acre	lb/acre
Anhydrous Ammonia	185.9b	30.3a	3225bc	16.3b	118.6b	18.5b	137.1bc
Urea	197.8b	25.9a	3478b	20.1ab	131.5b	19.4b	150.9b
28%	177.9b	27.2a	2728c	18.5ab	114.0b	13.2bc	127.1c
Turkey Manure	232.3a	27.2a	4825a	27.8ab	158.2a	33.1a	191.4a
Control	112.2c	30.1a	3351bc	32.1a	44.5c	9.5c	45.0d

Means within a column followed by the same letter are not siognificantly different using Duncan's Multiple Range Test (α=0.1).

Table 3. Response of potato tubers to different nitrogen sources.

Nitrogen Source	Culls	Ones	Twos	Jumbo	Knobs	Market‡	Total	Vine Yield
	---------------cwt/ac---------------							lbs/ac
Anhydrous Ammonia	35.4a†	157.2b	214.8a	24.3a	16.8b	372.0a	448.5ab	1775b
Urea	29.0a	185.1ab	188.8a	20.3a	46.0a	373.9a	469.1ab	1806b
28%	26.0a	183.9ab	189.3a	24.7a	16.0b	373.1a	439.9b	1505b
Turkey Manure	37.2a	208.6a	208.2a	21.3a	21.7b	372.0a	497.0a	2788a
Control	26.9a	72.7c	197.3a	2.5b	4.7b	269.9b	304.0c	628c

† Means within a column followed by the same letter are not significantly different using Duncan's Multiple Range Test (α=0.1).
‡ Market refers to marketable tubers which is the sum of ones, twos and jumbos.

Table 4. Some quality parameters and nitrogen uptake values along with moisture content of tubers.

Nitrogen Source	Specific Gravity	Hollow Heart	Tuber N uptake	Tuber Water Content	Vine N uptake	Vine Water Content	Total N uptake
	g cm⁻¹	%	lbs / ac	%	lbs / ac	%	lbs / ac
Anhydrous Ammonia	1.0961a	12.5ab	153.9a	74.7a	26.4b	46.0cd	180.3b
Urea	1.0957a	8.3bc	170.8a	74.6a	26.3b	72.5ab	197.0b
28%	1.0948a	3.1c	160.0a	75.3a	24.0b	50.9bc	184.1b
Turkey Manure	1.0913b	6.3c	177.9a	75.9a	57.0a	87.2a	235.0a
Control	1.0934ab	15.6a	66.3b	75.0a	4.0c	27.7d	70.4c

Means within a column followed by the same letter are not significantly different using Duncan's Multiple Range Test (α=0.1).

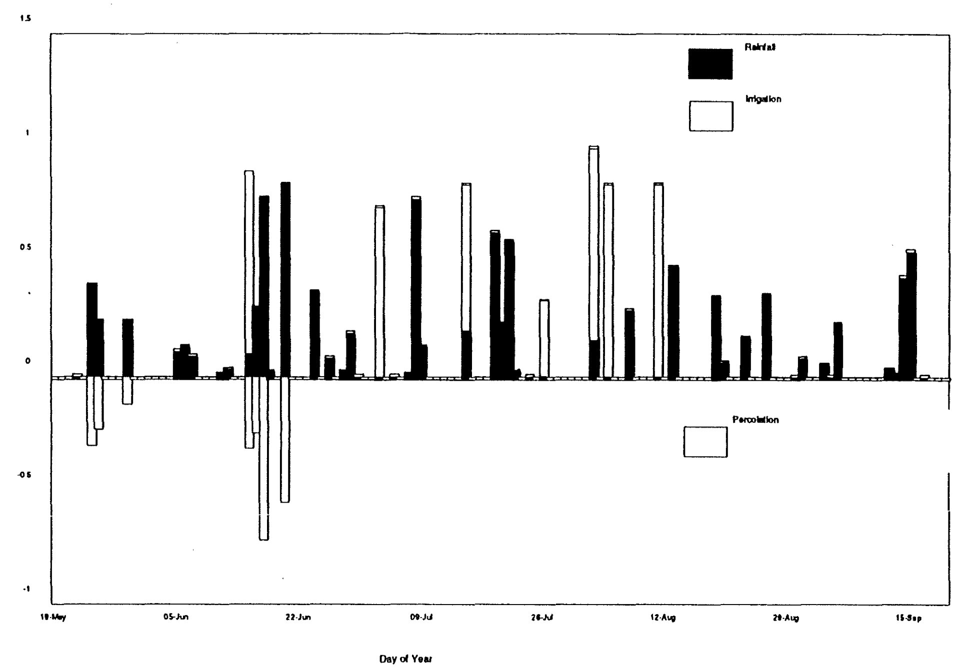


Figure 1 Rainfall and irrigation for the 1994 growing season. Percolation was calculated by a water budget approach using averaged values for water use for corn and potato.

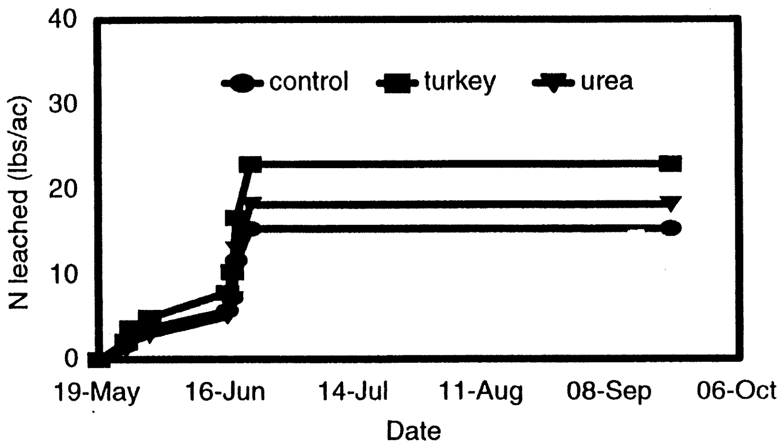


Figure 2: Cumulative N (principally nitrate) leached under corn plots instrumented with suction cup samplers during 1994 growing season.

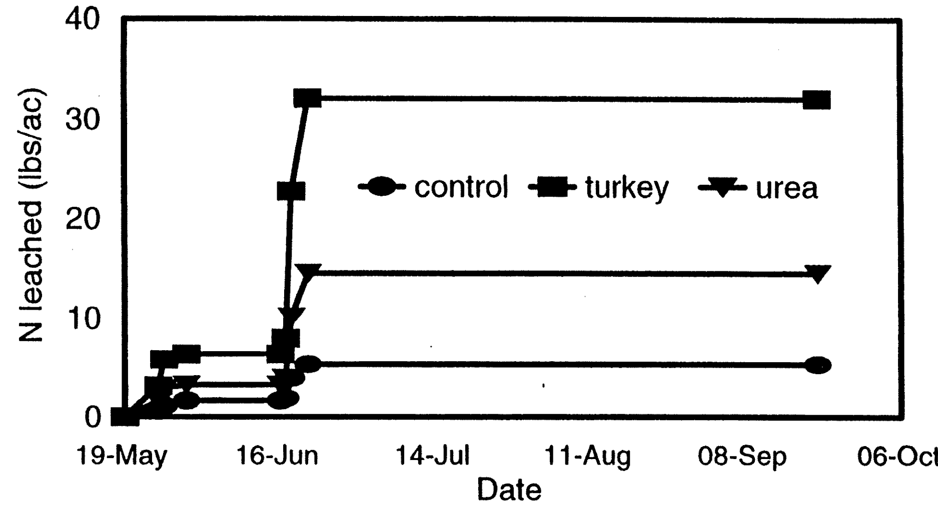


Figure 3. Cumulative N (principally nitrate) leached beyond the potato root zone during the 1994 growing season.

D. Title of Objective: Evaluate herbicide losses to groundwater under irrigated potato production.

D.1. Activity: Assess the fate and transport of herbicides used in irrigated potato productions under the management practices and soil and climatic conditions of the north-central Minnesota sand plain region and develop risk indices for these herbicides.

D.1.a. Context within the project: Use of herbicides for weed control is currently an integral part of the management practices in irrigated potato production. Since weeds are a major threat to potato production efficiency, effective weed control will be essential in the development of best management practices. If herbicides are to be used, it is crucial to determine the fate and transport of these chemicals as affected by the climatic and soil conditions and the fertilizer and soil management practices of the study region. The data generated will be used for testing the validity of the computer models developed under Objective E.

D.1.b. Methods: The field plots set up for evaluating the BMP for irrigated potato production (under Activity C.1.) will be used for assessing the fate of herbicides under the same conditions. Herbicides in common use in irrigated potato production (e.g.,linuron, metolachlor, and metribuzin) will be applied at standard rates, and soil and water samples taken for the nitrogen BMP studies under Activity C.1. will also be used to monitor the fate and transport of herbicides under the same field conditions. Extensive soil sampling will also be conducted at the end of the growing season and before the beginning of the following growing season. Laboratory methods will be tested for their efficiency in recovery and detection of residual herbicides in the soils. The data will be used to test the validity of the simulation model LEACHM for determining their risk indices.

D.1.c. Materials: The equipment needed for field sampling will be the same as those used for Activity C.1. Laboratory supplies.

D.1.d. Budget: $80,000, **Balance:** $0

D.1.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Field plot setup:	xxxx				
Field sampling/measurement:	xxxx		xxxx		xxxx
Laboratory analyses:	xxxxxxxxxxxxxxxxxxxxxxxx				
Result evaluation/model validation:	xxxxxxxxxxxxxxxxxx				

D.1.f. Status: We have completed a two-year study to monitor the fate and transport of herbicides in soil in a center-pivot irrigated field under commercial potato production at Park Rapids, Minnesota. This field site is the same as that described under C.1 for nitrate monitoring under the irrigated potato demonstration project. The soil at the experimental site is a Verndale sandy loam. Metolachlor and metribuzin were surface-applied according to standard production practices over the entire field. During the first year, 24 sampling stations were installed in the field which was set up to compare a conventional and a modified nitrogen fertilizer management strategy. Each water sampling station consisted of a set of stainless steel suction tubes buried at 135 cm (4.5 ft) below the soil surface either directly underneath a potato hill or underneath a row between the hills. Soil samples were collected in 15-cm (6-inch) increments down to the 90-cm (3-ft) depth. Water samples were collected one day after each significant rainfall event during the growing season, which is sufficient time for free drainage to complete in this soil. On each sampling date, not all stations yielded sufficient water for a proper analysis. Only those stations yielded more than 50 mL of water were stored for determination of the metribuzin and metolachlor concentrations. During the growing season of 1993, water samples were collected on 19 occasions. In addition, soil samples were taken from the differently managed parts of the study field 5 times: at planting, twice during the growing season, immediately after harvest, and one year later just before the next growing season.

Results from analyses of the 1993 samples indicate that both metolachlor and metribuzin were present sporadically at detection-limit levels of a few ppb concentration in some water samples. These occurrences were occasional and without any regular pattern. No detectable amount of metribuzin or metolachlor was found in any of the soil samples, except one, below the 30-cm depth. The detection limit of soil analysis is 5 ppb. Water analysis is more sensitive than soil analysis since we can analyze a large volume of water more readily than a large volume of soil. The quantity of pesticides detected in water, if converted to the soil basis, would be below the detection limit of the most sophisticated analytical instrument available.

To validate the observations made under field conditions of 1993, the monitoring study on herbicide movement under irrigated potato was repeated during the 1994 growing season in a field adjacent to the 1993 study field in Park Rapids. The 1994 potato field was in rye grass in 1993. Although the 1993 data showed a rapid initial dissipation of both metribuzin and metolachlor in the soil under field conditions, soil sampling frequency was insufficient to estimate the kinetics of dissipation or to ensure that no rapid leaching of these two chemicals took place. In the 1994 study, soil samples were taken at three-day intervals and analyzed for metribuzin and metolachlor contents without long delays. The results obtained verified the previous year's observations in that the dissipation of these two chemicals were initially rapid, with little or no observed downward leaching during the growing season.

To further verify the field observations, laboratory experiments were designed to study the degradation characteristics of metolachlor and metribuzin in soil taken from the same field and incubated under controlled conditions. Although environmental variables affecting herbicide degradation may not be the same under laboratory conditions as under field conditions, potential for degradation can be better assessed under controlled conditions, as laboratory studies provide data on degradation without complicated by leaching of the chemicals which can take place under field conditions. The kinetics of degradation observed under controlled laboratory conditions were similar to those observed in the field. Both herbicides degraded rapidly initially, but more slowly with time. Metolachlor appeared to degrade slower than metribuzin both in the laboratory and under field conditions.

The data obtained in the present study were consistent with those reported in earlier studies which were conducted at Becker, MN on a Hubbard loamy sand soil, as well as with other reported findings in the literature (see the detailed report for references). Neither herbicide was transported to any significant degree, but both tended to remain in the soil to some degree by the end of the growing season. We have accumulated in the last several years a wealth of data on herbicide fate and behavior in the sandy region of central Minnesota to establish guidelines for proper use of these herbicides. Because of the slower rates of degradation in the cool northern climate, judicious management of herbicide applications is essential to maintain environmental quality.

Movement and Degradation of Metolachlor and Metribuzin in North Central Sand Region of Minnesota under Irrigated Potato Production

J. M. Xu, W. C. Koskinen, H. H. Cheng, C. Rosen, and R. H. Dowdy

ABSTRACT

Field studies were conducted to determine the dissipation and movement of metribuzin and metolachlor applied at conventional rates to a Verndale sandy loam soil in north-central Minnesota under an irrigation potato production in 1993 and 1994. The rapid dissipation of both metribuzin and metolachlor was found during the initial 10 to 15 days in both years, >70% of applied herbicide dissipated during this period. Both herbicides had higher concentrations and dissipated more rapidly in furrow than in row. From 10 to 15 days after application up to the end of growing season in both years, the levels of both herbicides decreased slowly with time. Metolachlor dissipated at a slower rate than metribuzin in surface soil, and could carry over to the next cropping season. Metribuzin and metolachlor were detected in only 6 and 1 of 154 soil samples in 1993, and in 3 and 4 of 225 soil samples in 1994, taken from 15 to 75 cm, respectively. Fifty to 67% of water samples from suction samplers at 135-cm depth contained detectable levels (>0.4 µg L^{-1}) of herbicides in both years. The mean concentration of all metribuzin and metolachlor detections in water samples was 3.1 and 3.0 in 1993, and 1.5 and 1.7 µg L^{-1} in 1994, respectively. Under laboratory conditions degradation of both herbicides was much slower than their dissipation in field in the Verndale sandy loam soil. Therefore, it appears leaching may be an important dissipation pathway for metribuzin and metolachlor under irrigated potato production.

INTRODUCTION

Metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one] and metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] are two herbicides commonly used for weed control in potato, soybean and other crops. These herbicides have been listed as having moderate potentials for persistence in soil and for leaching to ground water (USEPA, 1988). Both metribuzin and metolachlor have been reported to move downward through soils into ground water in the United States and other countries (Bowman, 1989, 1990; Frank et al., 1990; Kross and Hallberg, 1989; LeBaron et al., 1988; USEPA, 1988; Williams et al., 1988).

Transport of metribuzin and metoachlor through soil profiles into ground water is governed primarily by transformation and retention processes. Factors capable of decreasing retention and transformation of metribuzin and metoachlor in surface soils would increase their potential for downward transport. For instance, metribuzin and metoachlor were more strongly sorbed and therefore moved slower in soils with higher organic matter and clay contents compared to sandy soils with low organic matter (Braverman et al., 1986; Huang and Frink, 1989; Obrigawitch et al., 1981; Peter and Weber, 1985; Savage, 1976; Sharom and Stephenson, 1976; Weber and Peter, 1982). Increasing soil pH also increased the movement of metribuzin by decreasing sorption (Ladlie et al., 1976). An inverse relation of metribuzin sorption to soil water content (Savage, 1976; Scott et al., 1974) implied that there was a high potential for leaching of herbicides through soil if heavy rainfall or excessive irrigation occurred. Bowman (1988) reported that no or limited movement of metolachlor occurred in Plainfield sand just receiving 60 mm rainfall during the first week after herbicide application, but metolachlor moved downward as deep as 40 cm after 111 mm of combined irrigation and rainfall.

Persistance of metribuzin and metolachlor in soils is low to moderate depending on soil type, tillage management and environmental factors. It has been shown that the half-life of metribuzin in soils ranged from 30 to 45 d (Burgard et al., 1994; Hyzak and Zimdahl, 1974; Nicholls et al., 1982; Walker, 1978; Weed et al., 1995), while that of metolachlor ranged from 24 to 108 d (Bowman, 1988, 1989, 1990; Burgard et al., 1993; LeBaron et al., 1988; Walker and Zimdahl, 1981). Previous studies also have indicated that degradation through microbial activity appears to be the primary pathway for transformation of both metribuzin and metolachlor in soil (Burgard et al., 1993, 1994; Weed et al., 1995).

Soil temperature plays a major role in determining rates of microbial degradation. For instance, dissipation half-life of metribuzin was 16 days at 35 °C and 377 days at 5 °C (Hyzak and Zimdahl, 1974). Degradation in subsurface soils is generally reported to be slower than in surface soils (Bouchard et al., 1982; Jones et al., 1990). Temperature and moisture have been shown to affect degradation in subsurface soils (Bouchard et al., 1982). Decreased microbial populations and activities in subsurface soils compared to surface soils result in a decreased rate of degradation (Moorman and Harper, 1989).

North central Minnesota is an important region for commercial potato production, but the soils have a high potential for leaching of herbicides to ground water. Coarser texture soils are extensively distributed in this area, which are good media for growing potatoes. Soils are often characterized by low water holding capacity and rapid drainage, and need to be irrigated frequently during the growing season from May to August. The lower annual mean temperature in this region would reduce the biological degradation of herbicide in soil. Therefore, as herbicide persistence increases, the potential for herbicide leaching also increases. Thus, the potential for herbicides leaching in northern climates is probably higher than in eastern climate locations with similar soil texture and organic carbon content and rainfall (Burgard et al., 1993). The combination of rainfall, irrigation and temperature would have a significant impact on leaching of herbicides in these soils.

The currently increasing concern about ground water contamination necessitates the assessment of the fate of herbicides applied to soils under irrigated crop production. The objectives of this study were to: (a) characterize the dissipation and movement of metribuzin and metolachlor applied at conventional rates under normal family-farm production conditions in the north central sand region of Minnesota under an irrigated potato production; and (b) assess the degradation process of metribuzin and metolachlor in the same soil under laboratory incubation conditions.

MATERIALS AND METHODS

Soil.

A two-year field study was conducted on a Verndale sandy loam soil at Park Rapids, north-central Minnesota, but in different fields for 1993 and 1994. Soil was well drained on outwash plains underlain by a yellowish brown calcareous sand. The previous crop was dry beans. Soil analyses, performed in duplicate, included: pH (1:1 soil:water), organic carbon, total nitrogen, cation exchange capacity (CEC) and particle size. Properties of 0 to 90-cm soil profile are given in Table 1. The texture of the profile varied from sandy loam to coarse sand. The organic carbon of the soil was moderate and decreased rapidly with depth. CEC of the profile also decreased rapidly with depth due to the decreasing clay and organic matter contents. Soil pH of the profile ranged from slightly acid at the surface to neutral in the subsoils.

Field dissipation studies.

Potatoes were planted on 30 April, 1993 and 4 May, 1994. Certified, A-size cut seed potatoes were mechanically sowed in rows at intervals of 28 cm. Distance between rows was 90 cm. Fertilizer applied during the growing season each year totaled 270 kg N ha^{-1}, 150 kg P ha^{-1}, and 250 kg K ha^{-1}. Suction cup samplers were installed on 8 May, 1993 and 10 May, 1994 by boring to the 135 cm depth with a soil probe of appropriate size in the furrow in 1993 and both in the row and in the furrow in 1994, pouring silica flour slurry down the hole, and pressing the ceramic cup of the tensiometer or suction sampler into the slurry. Bentonite clay was poured on the top of the suction cup samplers to prevent preferential flow along the tube-soil contact. The samplers were made of a Soilmoisture# Hi Flow (Soilmoisture Equipment Corp[1]., Santa Barbara, CA, 93105) ceramic cup mounted on the end of 5-cm o.d. and 45-cm long stainless steel tubing and 0.65-cm o.d. PTFE (teflon) access lines for sampler collection. On 12 May, 1993 and 23 May, 1994, herbicides were aerially applied as Turbo 8EC consisting of 15% metribuzin and 70% metolachlor at the rate of 34 fl. oz $acre^{-1}$. Irrigation water was applied by impact-type sprinklers during the growing season. Irrigation scheduling was based on the Checkbook Method of Wright and Bergsrud (1986). Potatoes were harvested on 7 September, 1993 and 15 September, 1994.

Soil samples were collected as intact 2.3 x 90 cm cores near the suction tubes between rows in 1993 and both in row and between rows in 1994. Soil samples were taken 1 d before and 5 times after herbicide application in 1993 and and 7 times after application in 1994. The soil samples were frozen at -15 °C, cut into 15-cm increments, and stored at -15 °C in polyethylene bags until extracted.

Water samples were taken from suction cup sampler tubes by applying a vacuum of 0.5 bars for a minimum of 12 h. Accumulated water was collected directly into brown glass bottles, previously rinsed with distilled, deionized water. Vacuum and air pressure were applied using a Soil Moisture Corporations Model C hand pump. Samples were collected one day after each significant rainfall and

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[1]Mention of a company name or trademark is for information purposes only and does not constitute or imply an endorsement or warrenty by the University of Minnesota or USDA-Agricultural Research Service.

irrigation event during the growing season. However, each sampling date, not all samplers yielded sufficient water for a proper analysis. Only those samplers that yielded more than 50 mL water were stored for herbicide analyses. Water samples were stored at 5 °C prior to pesticide extraction and analysis.

Laboratory degradation studies.

Laboratory degradation studies were conducted on two soils: Verndale sandy loam soil from Park Rapids, MN and Hubbard loamy sand soil (sandy, mixed Udorthentic Haploboroll) from Becker, MN. The latter has been described by Burgard et al. (1994), with 84% sand, 9% silt, 7% clay, 1.35% organic C, pH 5.9, and CEC 9.89 cmol kg^{-1}. Field-moist soil was passed through a 2-mm sieve and stored at 4 °C prior to use. The equivalent of 60-g oven-dried soil sample was added to 100-mL Erlenmeyer flasks, brought to moisture content of -33 kPa by addition of water, and spiked with metribuzin and metolachlor at 2 µg g^{-1} soil. The flasks were capped with stoppers and incubated at 28 °C in a dark incubator. Flasks were aerated weekly at which time water lost at sampling was replaced. The samples were analyzed for residual metribuzin and metolachlor on days 0, 3, 7, 14, 21, 28, 42 and 56 during incubation period. Four flasks were sampled at each sampling date. Herbicides were extracted from duplicate 10-g moist soil samples with 20 mL of 4:1 methanol:water (vol:vol) using a laboratory robotic system as described below and analyzed by gas chromatography.

Herbicide extraction and analyses.

Extraction of herbicides from water samples was performed using liquid-liquid partitioning. Sample volume varied between 50 and 250 mL depending on sampling date. One mL of toluene and 1 mL of 1 µg mL^{-1} alachlor standard in methanol as an surrogate were added to each water sample immediately prior to extraction. Water was extracted twice with dichloromethane (5:1 water: dichloromethane by vol). The combined dichloromethane extracts were dried with anhydrous sodium sulfate, evaporated on a rotary autosampler evaporator at 34 °C until toluene remained. The toluene solution was transferred into 2-mL vials and stored at 5 °C until analyzed for metolachlor and metribuzin by gas chromatography (GC).

Metribuzin and metolachlor were extracted from soil samples using a laboratoy robotic system and analyzed by gas chromatography (GC) (Koskinen et al, 1991). In brief, duplicate 10-g soil samples were weighed into a 50-mL centrifuge tubes and then extracted using 4:1 methanol:water (v:v). After evaporation of methanol, metribuzin and metolachlor were extracted from the water by C_{18}-SPE. Metribuzin and metolachlor were eluted from the packing with 1 mL methanol containing alachlor as the internal standard. GC separation was done using a 25-mL of 5% phenyl, 95% methyl silicone capillary column and the analysis using a nitrogen-phosphorus detector.

RESULTS AND DISCUSSION

Rainfall, irrigation and temperature.

The daily rainfall plus irrigation during the period after herbicide application up to potato harvest in field sites for 1993 and 1994 are shown in Figures 1c and 2c, respectively. The total rainfall was almost identical in 1993 (403 mm) and 1994 (404 mm). There were three occasions in 1993 when heavy rainfall events of more than 25 mm per day (on day 10, 42 and 64) occurred, and four occasions (on day 12, 24, 27 and 56) in 1994. The highest rainfall occurred on day 27 in 1994 when 102 mm rainfall was recorded. More frequent irrgation was needed for potato growth due to the relative short of rainfall at the latter stage in 1994. The irrigation totalled 36 and 136 mm in 1993 and 1994, respectively. The average air temperature during the growing season was 16.3 and 17.6 in 1993 and 1994, respectively.

Herbicide dissipation in surface soil.

Dissipation of both metribuzin and metolachlor in surface soil (0-15 cm) under field conditions did not follow first-order kinetics in 1993. The concentrations of metribuzin and metolachlor were 234 and 852 µg kg^{-1}, respectively, in surface soil samples taken 6 days after herbicide application (DAA) (Figure 1a). At 15 DAA, only 15 and 29% of the metribuzin and metolachlor levels observed 6 DAA, respectively, remained in surface soil. From 15 DAA up to 344 DAA, the levels of both herbicides in soil did not change significantly with time. The rapid dissipation of both herbicides during the 9-d period, 6 to 15 DAA, was due to degradation, leaching, or a combination of the two processes.

Soil samples were taken more frequently in 1994 than in 1993 and in row and in furrow separately. The levels of both herbicides in surface soil was higher in furrow than in row at 0 and 3 DAA (Figures 2a and 3a). The levels of metribuzin and metolachlor at 3 DAA were 89 and 216 µg kg^{-1} in row, and 419 and 563 µg kg^{-1} in furrow, respectively.

The heterogeneous distribution of herbicides between in row and in furrow during the initial 3 days after application can be attributed to the 17 mm rainfall closely following herbicide application. The readily desorbable herbicides could be washed from the row to furrow where it accumulated. The concentrations and losses of metolachlor and other herbicides in runoff were greatest when rainfall shortly followed herbicide application (Bowman et al., 1994; Gaynor et al., 1995). Herbicide residues remaining in the row should then be more tightly sorbed to soil and resistant to runoff and leaching, compared to herbicides in furrow being more mobile and available.

In the following 7-d period, 3 to 10 DAA, both metribuzin and metolachlor in furrow dissipated more rapidly than in row, but their concentration did not change significantly either in row and in furrow from 10 DAA up to the end of growing season. These were in agreement with the observations in 1993. At 10 DAA, soil metribuzin and metolachlor residues were 42 and 95% in row, and 10 and 21% in furrow, of the levels observed 3 DAA, respectively. Only the persistence of metribuzin in surface soil in row was found to follow first-order kinetics with a half-life time (DT_{50}) of 10 d. The rapid dissipation of both herbicides from 3 to 10 DAA in furrow might have resulted from degradation, leaching or a combination of the two processes. Both herbicides leached beyond the 15 cm surface soil, as evidenced by the frequency of detection of low concentrations (< 10 µg L^{-1}) for both metribuzin and metolachlor in water samples at from the 135-cm depth (Figures 1b, 2b, and 3b) and the detection of herbicides in several soil samples below 15 cm during the growing season in both years. The rainfall of 73 mm during the 9 d period from 6 to 15 DAA may have been the driving force of rapid dissipation of herbicides in 1993. Although the total rainfall of 23 mm during the initial 6 days after herbicides application in 1994, it may also have played a crucial role in the redistribution of herbicides in furrow. The rain water infiltrating the soil in the furrow during the initial 6 days would be far more than 23 mm of water on a flat surface due to the runoff from two sides of rows.

The degradation of herbicides might also be responsible for rapid dissipation of herbicides during the initial 10 to 15 d in both years. It has been reported that the time required for dissipation of 50% of the initial concentration (DT_{50}) in comparable soils ranged from 30 to 40 d for metribuzin (Burgard et al., 1994; Walker, 1978) and 21 to >106 d for metolachlor (Bowman, 1988; Burgard et al., 1993; Walker and Zimdahl, 1981). However, degradation of these two herbicides is temperature dependent and the average daily mean temperature during this period was relatively low, 10.2 and 15.4 °C in 1993 and 1994, respectively. Under temperature conditions ranging 10 to 15 °C in laboratory degradation studies, the half-life time of metribuzin and metolachlor in soils ranged from 110 to 298 d (Walker, 1978) and 59 to 71 d (Walker and Zimdahl, 1981), respectively. Therefore, it would appear that leaching rather degradation would be the main pathway for herbicide dissipation during the initial 10 to 15 days in both 1993 and 1994, but that degradation could contribute to the dissipation. After 10 to 15 d until the end of the growing season in both 1993 and 1994, the levels of both metribuzin and metolachlor decreased insignificantly or slowly with time. Little or no dissipation during such a longer period might be due to herbicide residues remaining being tightly bound to soil constituents, which would retard both leaching and transformation of herbicide.

Compared to metribuzin, metolachlor dissipated at a slower rate and resulted in more accumulation in surface soil in both 1993 and 1994. Residues of metribuzin and metolachlor at the end of the 1993 growing season were 6 and 121 µg kg^{-1} in surface soil, respectively; 2.6 and 14% of the levels observed 6 DAA, respectively. In 1994, metribuzin and metolachlor residues in surface soil at the end of growing season were 1.5 and 176 µg kg^{-1} for in row, and 3.1 and 128.5 µg kg^{-1} for in furrow, respectively. Residues of metribuzin were less than 2% of the levels observed 3 DAA for both in row and in furrow, and metolachlor residues were 81.6 and 22.8% of the levels observed 3 DAA in the row and in the furrow, respectively. Lower percentage of metribuzin residues compared to metolachlor at the end of the cropping seasons was also reported by Burgard et al. (1993, 1994). The detectable metolachlor in the 1993 field samples taken in the spring of 1994 indicated that metolachlor can carry over to the next cropping season. The longer persistence of metolachlor than metribuzin was also evidenced by the detectable levels of metolachlor in surface soil prior to herbicide application in both years since both herbicides were evenly applied in previous dry soybean crops in experimental field sites. The longer persistence of metolachlor than metribuzin in soil might be directly related to the stronger sorption of metolachlor to soil than metribuzin (Bouchard et al., 1982; Graham and Conn, 1992).

Herbicide movement in soil profile.

Detection of herbicides in soil profiles from 15- to 75-cm was infrequent and at extremely low levels (minimum detectable level of metribuzin and metolachlor > 10 μg g^{-1}). Out of 154 soil samples taken below 15 cm in 1993, detectable amounts of metribuzin and metolachlor were found in 6 and 1 samples, respectively. The soil detections were located in the 15 to 30 cm zone on 344 DAA (2 samples), in the 30 to 40 cm zone on 64 and 344 DAA, in the 45 to 60 cm zone on 344 DAA, and in the 60 to 75 cm zone on the 156 DAA for metribuzin and only in the 60 to 75 cm zone on 156 DAA for metolachlor. Only 3 and 4 of 225 soil samples below 15 cm in 1994 contained metribuzin and metolachlor, respectively. The 3 detections of metribuzin were located in the 15 to 30 cm zone (2 samples) and in the 45 to 60 cm zone in furrow on 10 DAA, respectively. The 4 detections of metolachlor were located in the 15 to 30 cm zone on 7 DAA and in the 30 to 45 cm zone on 3 DAA in row and in the 15 to 30 cm zone on 10 DAA in furrow. Based on these soil profile data, there is little consistent soil evidence of downward movement of herbicides in either 1993 or 1994. However, it was possible that herbicides had moved downward to below 75 cm in soil profile, as evidenced by detection of herbicides in soil water samples at the 135-cm depth (see next section). The detection limits of herbicide analysis are lower for water than for soil because of the increased amount of sample analyzed. Thus, these herbicides may be present at various depths of soil at levels below the analytical sensitivity in our experiment.

Herbicide in soil water.

In this study, only water samples with > 50 mL on each sampling date were used to determine the concentration of herbicides. There was a total of 228 and 159 effective water samples in 1993 and in 1994, respectively. Of total effective water samples, 54% and 67% of water samples contained detectable levels (>0.4 μg L^{-1}) of metribuzin, and 59% and 50% of water samples detectable levels of metolachlor (>0.4 μg L^{-1}), in 1993 and in 1994, respectively. Detectable levels of metribuzin has been reported at the 150-cm water samples in a field study although the frequency of detection was extremely low (Burgard et al, 1994). None of water samples taken prior to herbicides application had detectable metribuzin and metolachlor. This indicated that both metribuzin and metolachlor applied on soil surface at normal commercially used application rates could move downward to or beyond 135 cm depth during and after the growing season in the Verndale sandy loam soil.

Metribuzin and metolachlor rapidly leached to the 135 cm depth. In the two years, 11 of 15 water samples taken at 12 DAA contained detectable levels of metribuzin and metolachlor. The total rainfall during the initial 12 days was 63 and 58 mm in 1993 and 1994, respectively. Of special significance are the rainfall events of 41 mm on 10 DAA in 1993 and of 35 mm on 11 DAA in 1994 which could be attributed to cause the downward movement of herbicides. Rapid movement of herbicides is consistent with macroporous flow of water occurring to the 135 cm depth. A pattern of herbicides detected 1 to 2 days after a rainfall event was observed between herbicide levels in water samples with time and daily rainfall and irrigation with time in both years (Figures 1, 2, and 3).

The maximum detected concentration was 23 μg L^{-1} for metribuzin (49 DAA, 1993) and 28 μg L^{-1} for metolachlor (15 DAA, 1993) except one sample on 63 DAA in 1993 containing 111 μg L^{-1} metolachlor. The levels of both herbicides in water samples were extremely low and far below the EPA health advisory levels of 175 and 100 μg L^{-1} for metribuzin and metolachlor, respectively. The mean concentration of all metribuzin and metolachlor detections was 3.1 and 3.0 in 1993, and 1.5 and 1.7 μg L^{-1} in 1994, respectively.

Although the detection for both metribuzin and metolachlor in water samples was frequent, the detected levels at different sampling dates can not be compared quantitatively. For instance, heavy rainfall events could certainly lead to the downward movement of more herbicides from soil surface, but the concentration of herbicides in water samples may not be higher due to the large volume of rainfall. However, these detected data can be used to determine the difference between metribuzin and metolachlor in the same water samples and between in row and in furrow samples taken on the same sampling date. The concentrations of both herbicides were relatively higher in furrow than in row water samples in 1994 (Figures 2b and 3b). The mean concentration of all metribuzin and metolachlor detections was 2.5 and 2.0 μg L^{-1} in furrow and 1.1 and 2.0 μg L^{-1} in row, respectively. This was consistent with the higher levels of both herbicides in furrow surface soil samples than in row during the initial 3 days after application.

In spite of higher rate of metolachlor application than metribuzin, the concentration of metribuzin in water samples was higher than that of metolachlor in 1993 as well as for furrow water samples in 1994. This could be explained by higher affinity of metolachlor to soil than metribuzin as indicated by higher Kd and Koc values (Burgard et al, 1993, 1994; Graham and Conn, 1992).

Laboratory degradation studies.

Laboratory degradation of metribuzin and metolachlor is shown in Figures 4 and 5. Both metribuzin and metolachlor degraded rapidly in soil during the initial 7 d, 35-40% of applied herbicides degraded. Degradation then proceeded relatively slowly until day 56 when the experiment ended. During the 49-d period about 30% of the applied metribuzin and metolachlor degraded. Slightly greater amounts of metribuzin degraded than metolachlor.

To facilitate comparison to other studies, a first-order degradation rate equation was used to describe the degradation of both metribuzin and metolachlor. The calculated 50% dissipation times (DT_{50}) for metribuzin and metolachlor were 22 and 30 d, respectively, in Verndale sandy loam soil. However, DT_{50} for both metribuzin and metolachlor was less than 10 to 15 d in the same soil under field conditions. It appears that the dissipation of herbicides in the Verndale sandy loam soil under field conditions was not primarily due to degradation as evidenced by faster dissipation in the field at low average air temperature (10.2 to 15.4 °C) during the initial 10 to 15 d after herbicide application in field sites compared to slower degradation in laboratory studies at 28 °C.

Degradation was only slightly faster in the Verndale soil than in the Hubbard soil used in the studies of Burgard et al (1993, 1994) under identical laboratory conditions. However, in the field studies of Burgard et al (1993, 1994) there was a 19-d lag phase before dissipation began.

SUMMARY

It appears that metribuzin and metolachlor have the potential to leach through the soil profile under irrigfated potato production in the Verndale loamy sand soil. However, it is difficult to say to what extent they will leach and how much will leach. While laboratory studies on two Minnesota loamy sand soils showed similar sorption and degradation processes, field experiments showed different dissipation results. The differences in the field are presumeably due to differences climatological parameters or to subtle differences in physical and chemical properties of the soils or both. The next step to elucidate disspation pathways and processes will be to use solute transport simulation models. Sensitivity analyses will determine the impact of different variables on the dissipation of these two herbicides, the results of which can be used to extrapolate potential leaching to other Minnesota soils under irrigated potato production

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REFERENCES

Bouchard, D.C., T.L. Lavy, and D.B. Marx. 1982. Fate of metribuzin, metolachlor, and fluometuron in soil. Weed Sci. 30:629-632.

Bowman, B.T. 1988. Mobility and persistence of metolachlor and aldicard in field lysimeters. J. Environ. Qual. 17:689-694.

Bowman, B.T. 1989. Mobility and persistence of the herbicides atrazine, metolachlor, and terbuthylazine in Plainfield sand determined using field lysimeters. Environ. Toxic. Chem. 8:485-491.

Bowman, B.T. 1990. Mobility and persistence of alachlor, atrazine and metolachlor in Plainfield sand, and atrazine and isazofos in Honeywood silt loam, using field lysimeters. Environ. Toxic. Chem. 9:453-461.

Bowman, B.T., G.J. Wall, and D.J. King. 1994. Transport of herbicides and nutrients in surface runoff from corn cropland in southern Ontario. Can. J. Soil Sci. 74:59-66.

Braverman, M.P., T.L. Lavy, and C.J. Barnes. 1986. The degradation and bioactivity of metolachlor in the soil. Weed Sci. 34:479-484.

Burgard, D.J., R.H. Dowdy, W.C. Koskinen, and H.H. Cheng. 1994. Movement of metribuzin in a loamy sand soil under irrigated potato production. Weed Sci. 42:446-452.

Burgard, D.J., W.C. Koskinen, R.H. Dowdy, and H.H. Cheng. 1993. Metolachlor distribution in a sandy soil under irrigated potato production. Weed Sci. 41:648-655.

Frank, R., H.E. Braun, B.S. Clegg, B.D. Ripley, and R. Johnson. 1990. Survey of farm wells for pesticides. Ontario. Canada 1986 and 1987. Bull. Environ. Contam. Toxicol. 44:410-419.

Gaynor, J.D., D.C. MacTavish, and W.I. Findlay. 1995. Atrazine and metolachlor loss in surface and subsurface runoff from three tillage treatments in corn. J. Environ. Qual. 24:246-256.

Graham, J.S. and J.S. Conn. 1992. Sorption of metribuzin and metolachlor in Alaskan subarctic agricultural soils. Weed Sci. 40:155-160.

Huang, L.Q. and C.R. Frink. 1989. Distribution of atrazine, simazine, alachlor, and metolachlor in soil profiles in Connecticut. Bull. Environ. Contam. Toxicol. 43:159-164.
Hyzak, D.L. and R.L. Zimdahl. 1974. Rate of degradation of metribuzin and two analogs in soil. Weed Sci. 22:75-79.
Jones, R.E., P.A. Banks, and D.E. Radcliffe. 1990. Alachlor and metribuzin movement and dissipation in a soil profile as influenced by soil surface condition. Weed Sci. 38:589-597.
Koskinen, W.C., L.J. Jarvis, R.H. Dowdy, D.L. Wyse, and D.D. Buhler. 1991. Automation of atrazine and alachlor extraction from soil using a laboratory robotic system. Soil Sci. Soc. Am. J. 55:561-562.
Kross, B.C. and G. Hallberg. 1989. Iowa statewide rural well water survey: Summary of statewide results and study design. Iowa Dep. Nat. Res. and Univ. Iowa. 3 pp.
Ladlie, J.S., W.F. Meggitt, and D. Penner. 1976. Effect of soil pH on microbial degradation, adsorption, and mobility of metribuzin. Weed Sci. 24:477-481.
Lebaron, H.M., J.E. Mcfarland, and B.J. Simoneaux. 1988. Metolachlor. Pages 335-382 in R.C. Kearney and D.D. Kaufman, eds. Herbicides: Chemistry, degradation, and mode of action. Vol. 3. Marcell-Dekker, New York.
Moorman, T. B., and and S.S. Harper. 1989. Transformation and mineralization of metribuzin in surface and subsurface horizons of a Mississippi Delta soil. J. Environ. Qual. 18:302-306.
Nicholls, P.H., A. Walker, and R.J. Baker. 1982. measurement and simulation of the movement and degradation of atrazine and metribuzin in a fallow soil. Pestic. Sci. 12:484-494.
Obrigawitch, T., F.M. Hons, J.R. Abernathy, and J.R. Gipson. 1981. Adsorption, desorption, and mobility of metolachlor in soils. Weed Sci. 29:332-336.
Peter C.J. and J.B. Weber. 1985. Adsorption, mobility, andefficacy of alachlor and metolachlor as influenced by soil properties. Weed Sci. 33:874-881.
Savage, K.E. 1976. Adsorption and mobility of metribuzin in soil. Weed Sci. 24:525-528.
Sharom, M.S. and G.R. Stephenson. 1976. Behavior and fate of metribuzin in eight Ontario soils. Weed Sci. 24:153-160.
Scott, H.D., R.E. Phillips, and R.F. Paetzold. 1974. Diffusion of herbicides in the adsorbed phase. Soil Sci. Soc. Am. J. 38:558-562.
USEPA. 1988. Pesticide Fact Book. U.S. Environ. Prot. Agency. U.S. Gov. Printing Off., Washington, DC. Pages 522-529.
Walker, A. 1978. Simulation of the persistence of eight soil applied herbicides. Weed Res. 18:305-311.
Walker, A. and R.L. Zimdahl. 1981. Simulation of the persistence of atrazine, linuron and metolachlor in soil at different sites in the USA. Weed Res. 21:255-265.
Weber, J.B. and C.J. Peter. 1982. Adsorption, bioactivity, and evaluation of soil tests for alachlor, acetochlor, and metolachlor. Weed Sci. 30:14-20.
Weed, D.A.J., R.S. Kanwar, D.E. Stoltenberg, and R.L. Pfeiffer. 1995. Dissipation and distribution of herbicides in the soil profile. J. Environ. Qual. 24:68-79.
Williams, W.M., P.W. holden, D.W. Parsons, and M.N. Lorber. 1988. Pesticides in groundwater data base. 1988 Interim Report. U.S. EPA, Office of Pesticide Program, Washington, DC.
Wright, J. and F. Bergsrud. 1986. Irrigation scheduling: Checkbook method. AG-FO-1322. Univ. Minnesota Ext. Serv., St. Paul, MN. 10 pp.

Table 1. Selected physical and chemical properties of Verndale sandy loam soil

Depth	pH	OC	CEC	Sand	Silt	Clay
cm		%	cmol kg^{-1}		------------%----------	
0-15	5.9	1.07	9.6	76.9	14.1	9.0
15-30	6.5	0.45	5.7	77.1	13.9	9.0
30-45	6.9	0.13	2.8	89.2	6.6	4.2
45-60	7.2	0.05	1.6	95.9	2.2	1.9
60-75	7.1	0.04	1.2	97.2	1.3	1.5

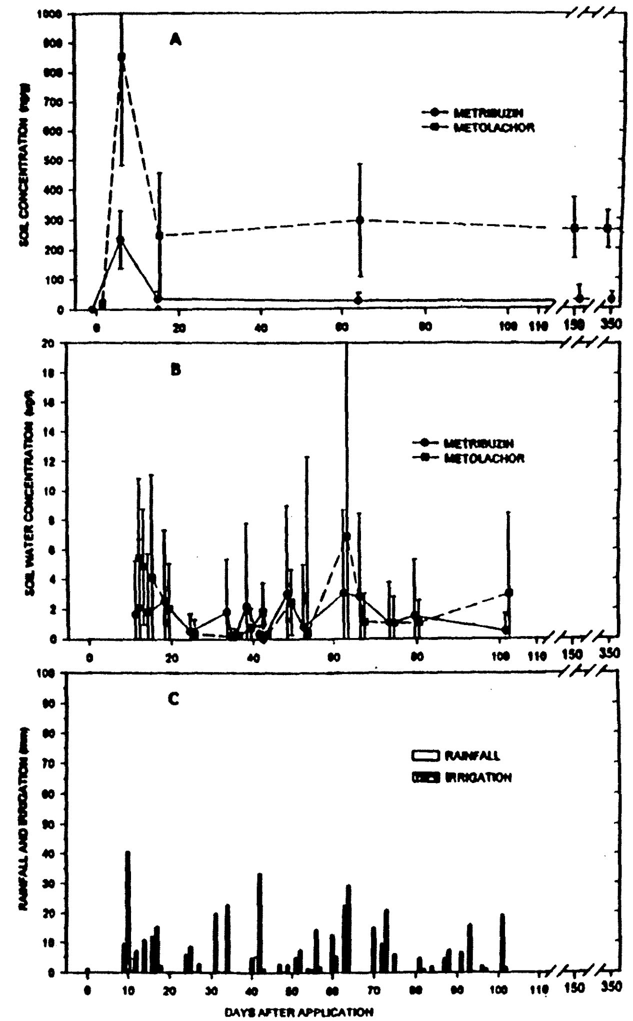

Figure 1. 1993 metribuzin and metolachlor field experiment: A) field dissipation; B) herbicide concentration in soil water suction samplers; C) total rainfall and irrigation.

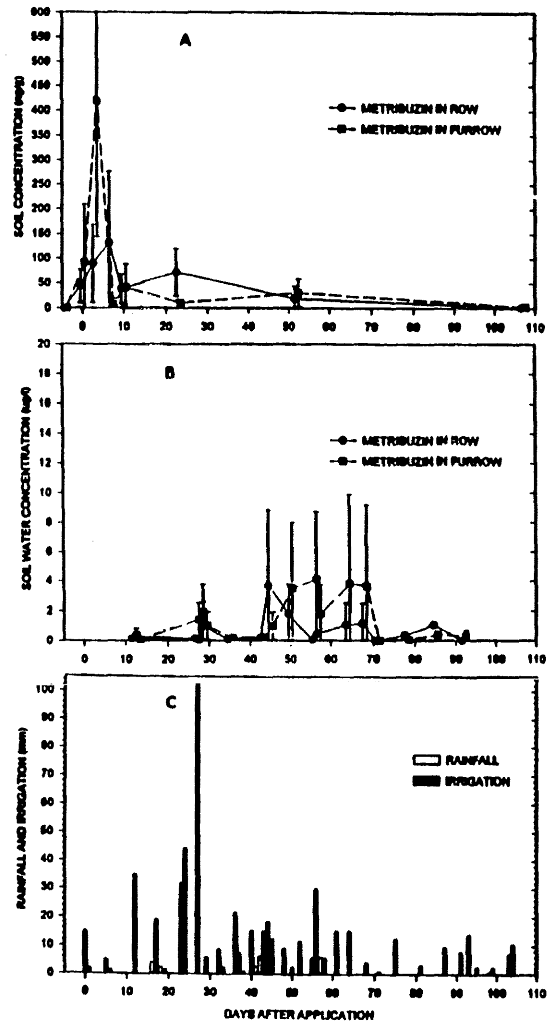

Figure 2. 1994 metribuzin field experiment: A) field dissipation; B) herbicide concentration in soil water suction samplers; C) total rainfall and irrigation.

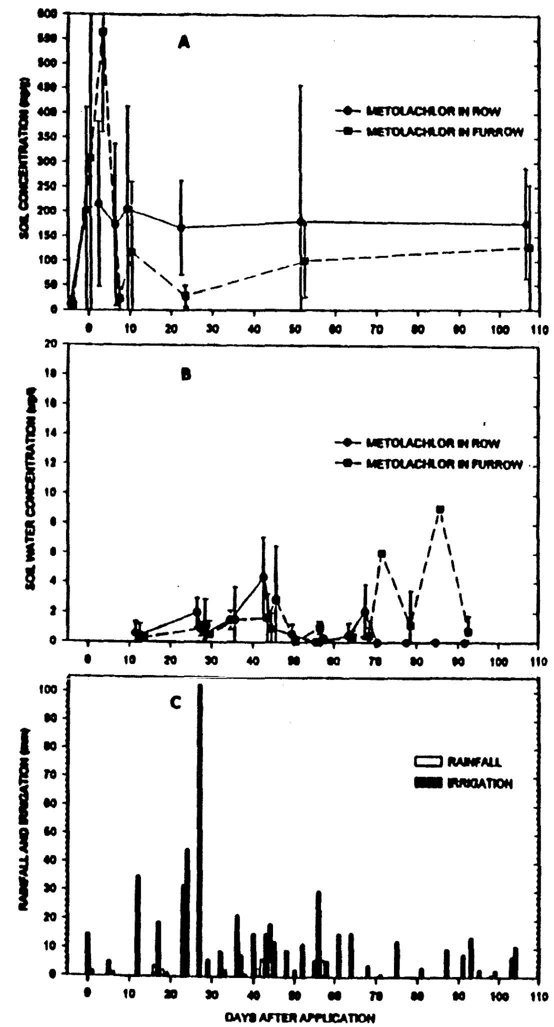

Figure 3. 1994 metolachlor field experiment: A) field dissipation; B) herbicide concentration in soil water suction samplers; C) total rainfall and irrigation.

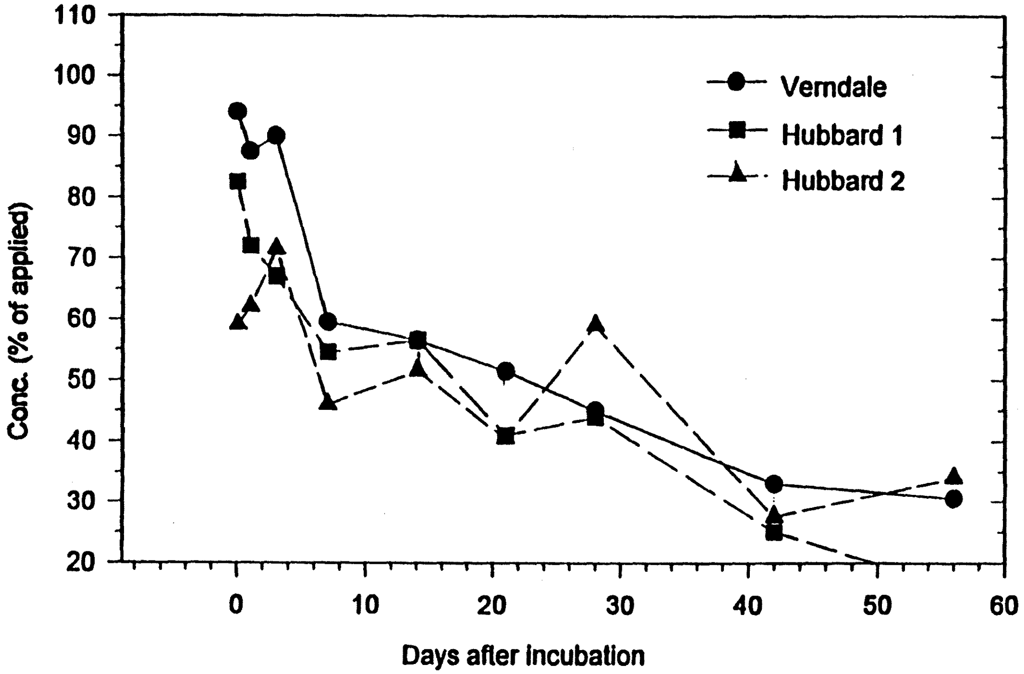

Figure 4. Laboratory degradation of metribuzin in Verndale and Hubbard soils.

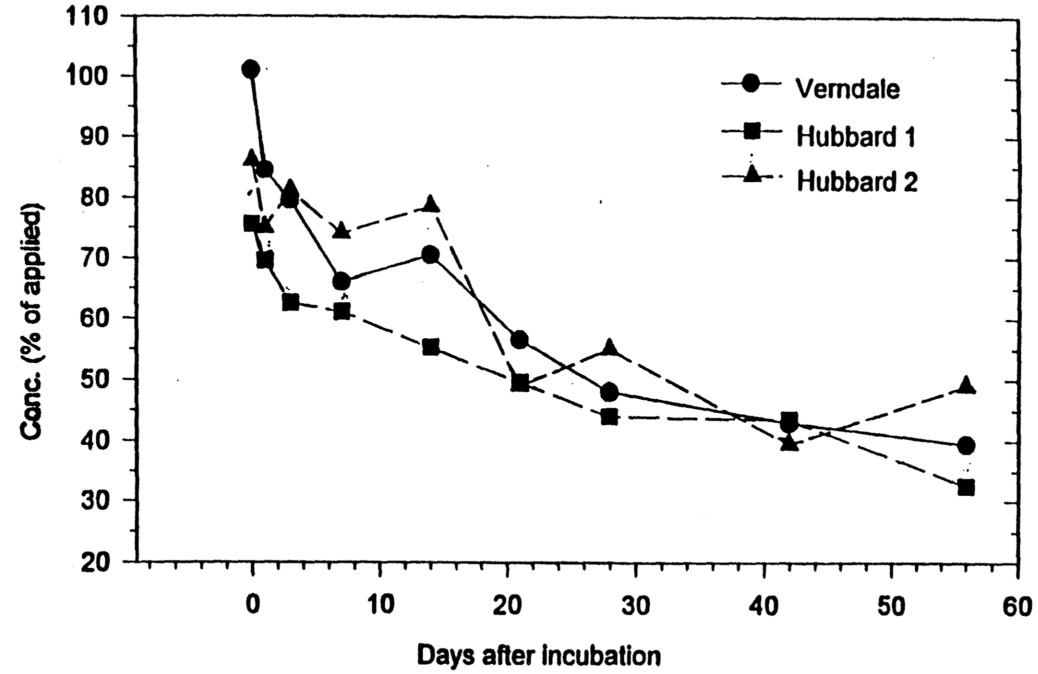

Figure 5. Laboratory degradation of metolachlor in Verndale and Hubbard soils.

E. Title of Objective: Develop computer models for BMPs that consider movement of water, nitrogen, and herbicides.

E.1. Activity: Mode of deposition of Minnesota Glacial Outwash soils and its influence on water flow.

E.1.a. Context within the project: Most of the models in the literature that deal with the transport of water and contaminants in soil assume a uniform movement of wetting front. These models include the CERES-Maize, SUBSTOR, and LEACHM that will be used in this study to assess the susceptibility of Minnesota Glacial Outwash soils to nitrate and herbicide leaching. Recently, it has been shown in the literature that there is a differential movement of water in sandy outwash soils. This differential movement is mostly due to soil heterogeneities, i.e., presence of fine layer in a coarse sandy soil. The level of differential wetting depends on the extent and the orientation of these fine layers. The focus of this objective is to identify soils where the wetting front movement is uniform and where there is differential wetting.

Procedures will be developed to identify soils with characteristics of differential wetting due to the soil heterogeneities. The procedures will be based on the relationship of wetting front movement to mode of deposition of fine layers during the development of these soils. Identification of soils with uniform wetting characteristics will help in the correct applications of CERES-Maize, SUBSTOR, and LEACHM models.

E.1.b. Methods: One soil in the Minnesota Glacial outwash region with known mode of deposition of fine layers will be used to develop procedures for identifying soils with uniform and differential wetting characteristics. The site will be located at the Staples Irrigation Center site at Staples, MN. Wetting front characteristics will be studies at several antecedent moisture conditions. These moisture conditions will be created by irrigating a site with sprinkler irrigation overnight and then starting the wetting fronts studies at various stages of drying over the next two weeks. The procedure for characterizing the wetting front advance will include diking several 1m x 1m plots, spraying the surface with food dye and then applying irrigation to move the food dye into the soil profile. Method of irrigation will include flood or sprinkler irrigation. Water will be applied at an equivalent rate of 2 times the 1.5m root zone field capacity. The water will be allowed to drain for 3-5 days. During this time the soil will be covered with a plastic sheet to prevent rain water from entering the soil. At the end of the drainage period, soil will be sampled at a regular grid to the bottom of the root zone for analysis of its water content. After water content sampling, the soils will be exposed at one edge of the plot and the position of the dye will be plotted on a clear plastic sheet extended along the width of the soil profile. Also, plotted will be any visible presence of soil heterogeneity such as fine sandy layers. This process will be repeated at several transacts of the treated plot. Traces of the wetting front positions will be synthesized to get a three-dimensional view of the wetting front position and the position of soil heterogeneities. Extent and orientation of these heterogeneities will be analyzed with respect to the perceived mode of deposition of these layers. The mode of deposition may include a uniform flat deposition of a fine sand layer over a coarse sand layer, uniform or discrete deposition of fine sand layer at various angles, or nearly vertical fine layer in a coarse layer. The position of these heterogeneities will also be used to develop simple model of predicting the position of the wetting front. The simple model will quantify the extra advance in wetting front that may occur due to the soil heterogeneity as compared to that predicted from the piston flow theory. The second parameter to be quantified will be the extra quantity of water that will flow past the average piston flow wetting front position. Efforts will be made to merge this simple model with CERES-Maize, SUBSTOR, and LEACHM models to extend their applicability to soils where differential movement of water contaminants occurs. Soil heterogeneities will also be sampled for particle size distribution. If there is enough soil thickness of fine layers, samples will also be taken to characterize water retention and hydraulic conductivity.

E.1.c. Materials: Food dye, transducers, plastic sheets, computers, printer, flat bed image analyzer.

E.1.d. Budget: $50,000, **Balance:** $0

E.1.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Establish experimental plots	xxxx	xxxx			
Characterize water movement	xxxx	xxxx			
Develop model which considers the heterogeneity in wetting front			xxxx		
Incorporate into models				xxxx	

E.1.f. Status: An evaluation of the potato growth/nitrate leaching simulation model SUBSTOR-Potato was conducted by comparing measured field data with simulated values for 1991 and 1992 (16 combinations of management and climate) in a sandy outwash soil (Verndale sandy loam - coarse loamy over sandy, mixed, frigid, Udic Argiborolls) of central Minnesota. The results of this work were summarized in the final report for an LCMR-funded project which ended in June 1993. In that study it was found that predicted yield, nitrogen (N) uptake, and nitrate-N leaching followed measured trends of increases with increased N application rate, however predicted values generally were not within one standard deviation of the measured data. Evaluation of irrigation management strategies using this model suggested that soil moisture depletions to about 40% of total water-holding capacity would result in higher yields and lower nitrate leaching compared to more frequent irrigation. Overall, these results show that the SUBSTOR model can predict relative trends in nitrate leaching, but needs further testing and validation before it can be adopted on a larger scale in Minnesota.

SUBSTOR-Potato, and most other mechanistic approaches to modeling solute transport, assume uniform infiltration across an area. Evaluation of such model predictions is complicated for situations where preferential transport is occurring. Preferential transport is situation where water infiltrates in only a few areas thereby bypassing a large fraction of the soil matrix. Preferential transport has been reported in sandy soils. Therefore we undertook the present study to evaluate the prevalence of preferential flow in the Verndale soil, and to determine if the occurrence of preferential flow could be related to depositional or pedogenic features observable in the soil. To do this we conducted a dye-tracing experiment using FD&C Blue #1 food dye. Experimental treatments included a combination of three initial soil water contents (WET, MEDIUM, and DRY) and three application rates (FLOOD, SPRINKLER-High, and SPRINKLER-Low) in an alfalfa field, plus two additional plots in an adjacent field with no history of alfalfa. We observed extensive preferential dye movement under FLOOD conditions, regardless of initial soil moisture or recent vegetation history. Preferential flow path (PFP) lengths resulting from the two SPRINKLER rates were much shorter. Within-plot variability was very high. The major initiators of PFPs were decayed roots, followed by the abruptness and topography of the boundary between the Ap and Bt horizons. Open burrows were not common, though they did cause extensive preferential flow in the two non-alfalfa plots. While the shorter PFPs observed with the sprinkler rates suggest that preferential flow is less important under unsaturated conditions, we caution that interpretation of dye traces must take into account variable dye retardation (relative to the wetting front) under different application rates, and due to variability in the amount of adsorption between horizons. In this study, dye traces discerned pathways and relative extent of preferential transport of this moderately sorbed chemical under the imposed treatments, but these dye pathways may not necessarily reflect patterns in movement of water or other chemicals.

The last part of this study was to evaluate the adsorption characteristics of the FD&C Blue #1 dye used in the field study. The specific objectives of this portion of our research were 1) to quantify the amount of equilibrium adsorption of FD&C Blue #1 food dye in the Ap, Bt, and C horizons of Verndale sandy loam ; and 2) to determine the relative amount of dye retardation compared to the wetting front under two different flow velocities, which approximate the FLOOD and SPRINKLER-High treatments in the field. Twenty four hour batch equilibration measurements resulted in values for the linearized Freundlich distribution coefficient (Kd) of 4.54, 25.59, and 4.32 L kg^{-1} for the Ap, Bt, and C horizons respectively. It was surprising to find greater adsorption in the subsoil (Bt) compared to the Ap horizon, it is often assumed that maximum adsorption will occur in the surface horizon which contains greater amounts of organic matter. Neither organic carbon nor clay content differences explained the variation. Experiments with repacked soil columns of each horizon showed that the dye is retarded relative to the wetting front, and that the extent of retardation depends on the flow velocity. In the Ap and C horizons about twice as much retardation was observed under unsaturated conditions (low flow velocity) compared to ponded conditions. Application rate had little effect on dye retardation in the Bt horizon - likely because the flow rate under ponded conditions was still very slow due to low hydraulic conductivity, thus allowing enough time to reach near-equilibrium conditions. Breakthrough curves of the dye and Br^- ion for the Ap soil showed that dye movement relative to Br^- ion is relatively slower at the lower flow velocity compared to ponded application. The occurrence of variable retardation as a function flow velocity has important implications for interpreting dye pathways as a surrogate of the pathways of water flow. In addition, knowing that there is increased adsorption in subsoil horizon(s) can further complicate the interpretation of dye patterns resulting from field experiments. Researchers using dyes as tracers of water movement need to consider these two factors when evaluating the results of studies that use dyes as tracers of water and solute movement. In conclusion, this study found that preferential transport does occur in this soil, especially if there is standing water at the soil surface.

E.2. Activity: Assessment of nitrate and herbicide leaching in Minnesota Glacial outwash soils.

E.2.a. Context within the project: Identification of best management practices that will minimize nitrate and herbicide leaching and characterization of soils according to the potential for leaching of agricultural chemicals require long-term (10-20 years covering several climatic cycles) data on crop yield, nutrient uptake and leaching of chemicals past the root zone for a whole series of management scenarios on various soil types. This type of information is currently not available for the Glacial Outwash soils of Minnesota. The cost involved for setting up experiments to gather this information would be prohibitive. One of the effective means of obtaining this type of data is through simulation models that integrate soil, climate, and management information to predict crop growth, availability, and movement of chemicals in the root zone. Though these models are based on the physical principles of water and solute movement in soil, they still need site and crop specific information. In other words, these models need testing and validation before they can be extensively used for whole series of soils, under various management and climatic conditions. Two of the crop-environment resource synthesis model for water and nitrate movement that are currently being validated are CERES-Maize and SUBSTOR. Both these models have same sub-models for soil processes; however, the former simulates maize growth whereas the latter simulates potato growth. The LEACHM model will be evaluated for estimating herbicide movement under the same conditions. The focus of this objective will be to use the validated models, along with the soil, climatic and current management practices data bases, to categorize soils as to their potential for nitrate and herbicide leaching and then, through simulations under various management scenarios, identify the best management practices that will minimize leaching. Currently, these models lack procedures to handle manure applied N. Based on the literature, sub models of manure mineralization will be added to the existing models.

The RZWQM-Root zone water quality model was considered for the present study because it is being applied to the MSEA sites. However, this model is used primarily for research purposes and needs much more sophisticated parameters that are currently not available for most soils around the United States. On the other hand, CERES-Maize and SUBSTOR models are management models and have been extensively tested both within and outside the United States. The inputs needed to run these models are relatively simple and readily available. At this stage, we need to test if the CERES family of models are capable of predicting the nitrate leaching from soils and under climatic conditions of the Central Sands of Minnesota. Since the goal of this study is to identify management practices that will minimize nitrate leaching, we believe the models belonging to CERES family will be more appropriate and will allow relatively easy extrapolation to various soils of the area after the model validation. However, the data from the experiment planned in this study will be available for testing and validation of RZWQM.

E.2.b. Methods: The validated models will be used to generate crop yield and NO_3 and herbicide leaching under existing management practices for several soils in the Minnesota Glacial outwash area. The soils will be selected based on the area starting with the most dominant soil type. Soils will be categorized in various categories depending upon the amount of NO_3 leaching or based on N lost in percolating water as a fraction of N applied. For example, the categories might be I, II, III, and IV corresponding to NO_3 losses of 0-10, 10-20, 20-30, and 30-40 kg/ha N, respectively, or these categories might represent 0-10, 10-20, 20-30, and 30-40% of N applied.

The validated models will also be used to generate crop yield and NO_3 leaching vs. N input curves for various management scenarios. The N input rate, where the crop yield levels off and the NO_3 leaching increases dramatically, will characterize the best N input rate for a given management practice. The amount of N lost at best N input rate for a given management practice will be used to categorize the soil under consideration. Various scenarios of management practices like N application rates, irrigation amount, timing of N and water application and source of N will be simulated to rate soils as to their effects on NO_3 leaching.

Various ratings of a soil will be compared to produce ranking of best management practices that minimize NO_3 leaching. Since NO_3 leaching for a given soil and management practice heavily depends upon the climate of the area, soil will be categorized at three probability levels (wet, average, dry) based on the climate of the area over the past 20-30 years.

The BMP's will be developed for corn and potatoes.

E.2.c. Materials: Micro computer and printing peripherals.
E.2.d. Budget: $44,000, **Balance:** $0
E.2.e. Timeline:

	7/93	1/94	6/94	1/95	6/95
Continued validation of models	xxxxxxxx				
Risk characterization of soils	xxxxxxxxxxxxxxxxxxx				
Summary and report				xxxx	

E.2.f. Status: A series of studies quantified the role of major factors such as climate, soils, and fertilizer and irrigation management on water percolation and nitrate and herbicide leaching through outwash soils in Central Sands of Minnesota. Typically, soils in the Central Sands of Minnesota are developed from glacial outwash parent material. These soils have low production potential because of low soil fertility and lower capacity to hold water. Precipitation alone cannot sustain most agricultural crops during the growing season. Since ground water is shallow and easily accessible, extensive areas have been brought under cultivation since the 1960's by supplementing crop water needs with irrigation. Major crops of the area are corn and potato. These crops have often been fertilized excessively to maximize yield. Shallow surficial aquifers in the Central Sands of Minnesota are also the source of drinking water supply for most of the communities in the area. Contamination of the groundwater by nitrate and herbicides is primarily because the soils are nonadsorbing and have low water holding capacities, resulting in deep percolation of rain or irrigation water down the soil profile.

In the first study, we used a hydrologic water balance computer model to identify the peak leaching periods and the corresponding amount of percolation based on long-term daily meteorological data, and to compute the annual excess precipitation and irrigation that may percolate through Minnesota outwash soils with various water holding capacities. As expected, result of this modeling showed that the percolation losses decrease with an increase in soil water holding capacity. The occurrence of percolation losses in this region is highest during spring and fall because of a limited loss of water by evapotranspiration.

Since soils and climatic factors cannot be easily manipulated, the only viable option available to minimize nitrate leaching from these soils is through the management of irrigation and fertilizer and herbicide application. In the next study, we tested and validated the CERES-Maize model under the soil and climatic conditions of the Central Sands of Minnesota, and then identify the management practices that can minimize nitrate leaching. The validation was done against the experimental data on corn yield, N uptake and N leaching for four fertilizer application rates and two irrigation schedules on Verndale sandy loam soil (coarse loamy over sandy, mixed, frigid, Udic Argiboroll) during 1991 and 1992 at Staples, MN. In general, simulated values were close to the observed data. Simulation with 31 years of climatic data showed that N leaching in these soils was mainly caused by excess irrigation or unexpected rains that may occur right after irrigation. Therefore in order to minimize N leaching, irrigation should be applied so that there was always some unfilled porespace in soil to capture the unforeseen rain that may occur after irrigation.

The simulation results also showed that for outwash soils of Minnesota, using yield goal to select N application rates is not appropriate because climate is a major determinant of the yield in the area. Also, the irrigation trigger of about 30-40% and fertilizer application of about 180 kg ha^{-1} are sufficient for achieving maximum corn yield. Irrigation trigger for potato production may be higher because potatoes are more sensitive to water deficit stress. We also developed a procedure to characterizes the risk potential of these soils to N leaching based on the output results of long-term simulation of CERES-Maize. The procedure identifies fertilizer and irrigation management practices best suited for maximum yield and minimum N leaching for a given soil and climatic condition.

Although the rates of herbicide applications must adhere to label specifications, thus less variable, their fate in the field is subject to soil management practices, especially when irrigation is used to supplement moisture for crop production. Water management is, therefore, critical to proper herbicide use under field conditions. The patterns of movement of metribuzin and metolachlor observed in the Verndale soil under field conditions are similar to those simulated by the CMLS (Chemical Movement in Layered Soil) Model for both the Verndale soil at Staples and the Hubbard soil at Becker, MN.

In the next two studies, we conducted a field and simulation studies to evaluate whether or not subsurface drip irrigation is a possible alternative in providing substantial unfilled pore space to hold water from unforeseen rains that might occur right after irrigation. The field experiment consisted of measuring hourly soil water content profiles with Time Domain Reflectometry (TDR) probes under growing potato plants in both sprinkler and drip irrigated plots in the Verndale soil at Staples, MN. Wetting and drying patterns showed that there was little water movement to the upper parts of the ridge in the drip irrigated plot. Under both furrow and just below the center of the ridge, there was a large change in water content during the full canopy period. This large change in soil water content under the furrow was due to a greater amount of infiltration as a result of water runoff from the ridge. Large changes in soil water content just below the ridge was due to more water reaching the base of the plant from stem flow and then most likely from preferential water transport through cracks created by the expanding tubers. Small changes in water contents just below the shoulder of the ridge compared to just below the furrow were due to higher runoff from the shoulder of the ridge and thus less water infiltration.

Experimental results suggested that water movement in the soil profile under a ridge-furrow system is a two-dimensional process. Since the experimental characterization of water movement in the soil profile under a ridge-furrow system for a whole range of treatments is expensive and time consuming, we used a mechanistic 2-dimensional model (SWMS_2D) to evaluate the role of stem flow, and the depth of drip placement on percolation losses in subsurface drip irrigation treatments. Using the SWMS_2D model, we also quantified the differences in percolation between the sprinkler and drip irrigated plots.

Simulation results showed that there was little water movement towards the upper part of the ridge when the drip was installed at 40 cm depth or deeper from the top of the ridge in the Verndale soil. This observation has important implications if drip irrigation is also used for application of fertilizer. Since the potato roots are not fully developed at the early stages of potato growth, the simulation results suggest that surface application of starter fertilizer would be better than the application of fertilizer through the drip line. Deeper placement of drip led to excess percolation due to higher hydraulic conductivity of C horizon whereas shallow placement potentially present problems of drip tape being ripped during potato harvest. Simulation results also showed that irrigation water applied through the buried drip could reduce the water percolation losses significantly compared to sprinkler irrigation method if a rain comes shortly after the irrigation.

E.3. Activity: Determine soil conditional probabilities for percolation on north-central Minnesota sandy soils. Field measurements and modeling to determine soil temperature and soil moisture.

E.3.a. Context within the project: Both water quality and sustainability issues can be addressed by implementing more precise production management practice strategies on the sandy soils of central Minnesota, particularly with respect to irrigation, nitrogen, and herbicide applications for potato and corn. Among the obstacles limiting implementation of such strategies is a lack of knowledge about highly variable climate and soil conditions which govern the utilization and efficiency of these three production inputs (water, fertilizer, and herbicides). Straight temporal probability distributions for important climatic and soil variables (i.e. moisture and temperature) are useful for strategic planning. However, early spring measurements of soil temperature and moisture provide a baseline for conditional probability functions to be determined which allow for both strategic and tactical plans to be made for applications of irrigation water, nitrogen fertilizers and herbicides which will best match environmental conditions and still allow yield goals to be achieved. More efficient use of resources and environmental stewardship might be realized from such practices.

E.3.b. Methods: Soil temperature and moisture models will be tested against field measurements to determine their relative accuracies on the sandy soil types of central Minnesota. Once tested and calibrated, these models will be used to calculate field working day probability functions for both the spring and the fall seasons. Using the state climate data base, a spatial analysis of field working day probabilities will be done. Using the models along with a network of soil moisture measurements, percolation rates will be estimated and examined over time to determine the probability functions over the course of the crop planting and fertilization season (primarily late April to mid June). Modeled hydrologic components such as rainfall rates, evaporation (and evapotranspiration), runoff and percolation rates will be tested against calculations from the automated weather station network. Lastly, specific spray occasion distributions will be determined for selected herbicide compounds. Testing for environmental conditions which meet label criteria should provide useful information for growers to better select herbicide

E.3.c. Materials: Nearly 40 climate stations are available for the central sand plains region of the state. Station measurement histories vary from 50 to 100 years, but are deemed sufficient to characterize both the spatial and temporal variability of important climatic and soil conditions. These data are available on the computerized state data base (CLICOM) in the Soil Science Department. In addition, automated weather stations which measure soil and atmospheric conditions in much more detail are providing daily and hourly data from 6 sites in the region. These will be used to test the accuracy of modeled soil temperature and moisture variables. One or two additional stations may be purchased to monitor conditions where field experiments will be done on objectives B, C, and D.

E.3.d. Budget: $41,000, **Balance:** $0

E.3.e. Timeline:	7/93 1/94 6/94 1/95 6/95
Inventory historical climatic data base	xxxxxxxxxxx
Field measurements	xxxxxxxxxxxxxxxxxxxx
Test models for temperature and moisture	xxxxxxxxxxxxxxxxxxxx
Compute probability distributions	xxxxxxxxxxxxxxxxxxxx
Evaluate applicability of probabilities and spray occasions	xxxxxxxxxxxxxxxxx

E.3.f. Status: Historical climatic distributions for six locations in the north-central region of Minnesota show some degree of spatial variability, primarily due to latitudinal position since the region stretches approximately 150 miles from south to north. The temporal, or year to year variability is much greater than the spatial variability. Extreme events such as very short growing seasons, 100 degree temperatures and 4 inch rainfalls generally occur less than five percent of the time and cannot be mediated by existing management practices anyway.

The only location with a soil temperature record of any length was Staples Irrigation Center (1983-1993). The temporal pattern in both the four inch and eight inch depth shows considerable variability in the early spring and fall periods, with lesser variability during the summer months. Average temperatures at a depth of four inches reach 50 degrees F or greater during the last week of April. This is sufficient to trigger more active mineralization rates from nitrogen sources in the soil and also indicates that crops sown in mid to late April should adequately germinate. The degree to which soil temperatures are moderated by irrigation is unknown on these soils, but may be useful to investigate in order to fine-tune site specific management of fertilizer and manure applications which supply nitrogen sources subject to mineralization rates highly regulated by a variable soil environment.

Soil moisture retention in the north-central sands is generally poor, especially in the near surface layers. Volumetric field capacity for soil moisture in many of these sands ranges from 15 to 18 percent, while volumetric wilting point moisture content ranges from 6 to 8 percent. This equates to an available water holding capacity ranging from 1.0 to 1.3 inches per foot of soil. A soil moisture submodel from CERES-Maize (1985), available through the Midwest Climate Center, was run on a composite climatic data set (using multiple stations) for north-central Minnesota covering the period from 1951-1993. The resulting temporal distribution of soil moisture in the region showed that beginning in mid July and lasting well into September, soil moisture levels in the top 60 inches are at their lowest levels, commonly less than half of available water holding capacity. In fact over a quarter of the time during late July and early August, available soil moisture values are less than 20 percent. This corresponds to the peak irrigation season for most crops in the region when rainfed soil moisture is supplemented heavily by overhead sprinkler applications.

Many irrigators in the north central sands use estimates of potential evapotranspiration on a daily basis coupled with monitoring soil moisture levels to help schedule irrigations during the crop season. However, little use is made of historical patterns of potential evapotranspiration and temporal soil moisture probabilities to critically look at irrigation design capacities. In addition, weather forecast probabilities are under-utilized in making decisions about when to apply irrigation as well as how much to apply. Probability of precipitation forecasts (POPs) and quantified precipitation forecasts (QPF) are available daily from the National Weather Service Forecast Offices in Minnesota, but are rarely used in irrigation decisions. Utilizing these information resources more fully should improve site-specific management of irrigation systems on the soils of north-central Minnesota. A pilot effort with some members of the North-Central Irrigators Association has been initiated to test this hypothesis.

Probability distributions for precipitation at the six climatic locations in the region, show that there is a twenty five percent chance of receiving 1.5 to 2.0 inches of excess (above average) rainfall during the months of June, July and August, the peak irrigation season. During the same period, there is a twenty five percent chance of having a rainfall deficit of 1.0 to 1.5 inches for any individual month. Frequencies for heavier one day rainfall events (0.5, 1, 2, and 3 inch quantities) were computed for the same set of climatic stations. They showed that on the average there are 5-6 one inch rainfall events per growing season, most of which occur in June, July and August. There are however a number of one inch or greater rainfall events which occur in May and September with a frequency of every two years, while similar heavy rainfalls in April and October occur with a frequency of about one year in three. These type of rainfalls may contribute more to leaching and runoff losses of nitrogen in the soil profile due to the absence of crop canopy that is more typical of these months. Best Management Practices (BMPs) for nitrogen in this area of the state already call for split applications to correspond more closely to crop need and uptake. This strategy alone can help compensate for the higher risk of leaching losses during these months. Precipitation events of 3 inches or greater occur across the region with a frequency of every 4-5 years and produce significant leaching losses regardless of the time of year.

Mechanical, cultural and chemical forms of weed control are used in the north-central region. The use of postemergence herbicides has been increasing in recent years, as producers have sought more flexibility in controlling weeds with a combination of methods. Late spring or early summer weed flushes missed by soil applied herbicides, cultivations or rotary hoes are often treated with specific postemergence compounds. Environmental conditions shortly before, during and after herbicide applications govern the efficacy of the compound in most cases as few herbicides are weather proof.

Spackman's method (1983) of defining spraying-occasions for herbicides was used to evaluate which of several environmental criteria were the most restrictive with respect to the use of postemergence compounds in the north-central region. Wind speed was by far the most restrictive climatic element in limiting spraying-occasions. The two wind criteria used for selecting spraying occasions were speeds less than 10 mph and speeds less than 5 mph, both of which are commonly recommended by agronomists or cited on label instructions. Using the hourly climatic records from Staples in 1994, the number of spraying occasions suitable for the use of postemergence herbicides from late May to late June were calculated. The number of spraying occasions which met the 10 mph wind speed criteria were six times more than the number which met the 5 mph criteria. This suggests opportunities to use any compounds which impose a risk associated with spray droplet or vapor drift are far fewer than for those which pose no such risk.

There are many opportunities to more fully utilize historical climatic data, soil moisture models, potential evapotranspiration estimates, weather forecast probabilities, and spraying occasion calculations in crop production management within the north-central region. Combined with greater utilization of soils maps and irrigation technologies, these information sources should be tested to evaluate their impact on site-specific management of irrigation water, nutrients and herbicides.

E.4. Activity: To establish a dialogue between soil scientists and potato producers through the information generated by a computer simulation model.

E.4.a. Context within the project: Maximum yield is safely achieved with excess irrigation and nitrogen fertilization; a practice which may entail the risk of nitrate leaching. There is always a risk of yield deficit when unforeseen climatic events turn optimal management into suboptimal water and N input. Risks associated with optimal agricultural managerial decisions will have to be fully appreciated by potato producers before they willingly "take that risk". Simulation models can predict yield and nitrate pollution for various managerial decisions and climatic events; thus providing a tool with which producers and soil scientists can select acceptable managerial risks.

E.4.b. Methods: Two potato fields will be selected from growers and/or the Anoka Sand Plain Water Quality Demonstration Project and/or the RD Offut Company, Park Rapids MN. Simulation will be performed by the model NCSWAP. Crop dry mass, and nitrogen and water content in soil for each field will be predicted daily on the basis of estimated climatic events and assumed managerial practices over a 10-day and 1-month horizon. Simulations will be updated (corrected) every 10 days on the basis of real climatic events and managerial practices. Simulated information will be used to discuss risks assumed and taken during the growing season; and to establish the advisability of using the computer simulation model as a managerial tool. Potato sap nitrate tests will be performed during the growing season. They will be correlated with actual and simulated data in order to establish the potential of this test to help growers in their managerial decision.

E.4.c. Materials: Electronic mail and/or FAX services will be needed between the St. Paul campus and the potato grower site. A portable high performance computer will be needed.

E.4.d. Budget: $16,500, **Balance:** $0

E.4.e. Timeline:

	7/93	1/94	6/94	1/95	6/95
Obtain initial field conditions	xxxx				
Simulation/dialogue		xxxxxx		xxxx	
Preliminary evaluation		xxxxxxxx			
Evaluation				xxxx	

E.4.f. Status: Computer simulation modelling was used to predict the nitrogen mass balance of the soil, water, and plant environment on a potato farm in Becker, MN. The model (NCSWAP) accurately forecasted a period of plant nitrogen stress during the 1994 season, and demonstrated how paradoxically there could be an increase in nitrate leaching. One outcome of this research is a recommendation for better irrigation practices, and higher crediting of field nitrogen sources.

NCSWAP operated in a real-time environment during the two growing seasons that farm nitrogen practices were analyzed. Climatic data and management decisions were updated continuously, and the feedback loop between grower and simulation was short. Off-season the model was validated using field data, and where needed, assumptions were modified. For instance, the model tended to overstate nitrate leaching, and this process was revised.

The model NCSWAP is a useful tool for field nitrogen management, and the mass balance approach also has potential as a teaching aid. The model can quickly and repeatedly test alternative nitrogen strategies, while demonstrating the relationship between various nitrogen sources and crop development. Application of this technology to site specific farming, however, is hampered by the models heavy data requirements.

SOLUTE TRANSPORT IN SANDY SOILS: POTATO MANAGEMENT MODELING AND FIELD EVALUATION OF PREFERENTIAL FLOW MECHANISMS USING A DYE TRACER

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL OF THE UNIVERSITY OF MINNESOTA
BY

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ABSTRACT

Ground water quality is a concern in areas of sandy soil in Minnesota. A computer simulation model for potato growth and nitrate leaching (SUBSTOR-Potato) was tested in 16 management-climate combinations in a sandy outwash soil. Predicted yield, N uptake, and nitrate-N leaching follow measured trends of increases with increased N application rate, however predicted values generally were not within one standard deviation of the measured data. Evaluation of irrigation management strategies using the model suggest that soil moisture depletions to about 40% of total water-holding capacity will result in higher yields and lower nitrate leaching compared to more frequent irrigation, but use of a longer weather record is suggested for specific management decisions.

A second study was under taken to evaluate the prevalence of preferential flow in this soil, using a dye-tracer (FD&C Blue #1) in the field. Treatments included three initial soil water contents and three application rates. Extensive preferential dye movement occurred under FLOOD conditions, whereas movement under the two SPRINKLER rates was shallower. The effect of initial moisture was minimal. Within-plot variability was very high. The major PFP-initiators were decayed roots, followed by the abruptness and topography of the Ap/Bt horizon boundary, and then open burrows (which were uncommon).

Analysis of the field data raised the question of whether the observed dye patterns as a function of application rate were due to patterns of water movement or due to effects of application rate on dye adsorption. Batch adsorption measurements found linearized Freundlich distribution coefficients (Kd) of 4.54, 25.59, and 4.32 L kg^{-1} were for the Ap, Bt, and C horizons respectively. Neither organic carbon nor clay content differences accounted for the variation. Flow experiments with repacked soils columns found about twice as much dye retardation with lower flow velocity conditions compared to ponded conditions in the Ap and C horizons, but had little effect on dye retardation in the Bt horizon. Therefore the occurrence of less deep preferential transport of the dye under lower application rates in our field study does not necessarily mean that there was less preferential water movement. Additional dye studies using multiple tracers would be useful. Increased adsorption in subsoil horizon(s) further complicates the interpretation of dye patterns resulting from field experiments. These factors need to be considered when evaluating the results of field dye studies.

SYNOPSIS

The research described in this dissertation spans three different levels. At the broadest level, I evaluated the suitability of a specific computer simulation model (SUBSTOR-Potato) for predicting potato yield and nitrate leaching in the Central sand plain region of Minnesota (Chapter 2). The 'big picture' application for using this model is to evaluate how potato production can be managed in this region to minimize the amount of nitrate leaching to ground water while not adversely affecting crop yields. Nitrate concentrations in the ground water have increased since the 1960's (Myette, 1984; Klaseus et al., 1988) and it is often attributed to the extensive potato production in the region. Potatoes are often given high nitrogen (N) fertilizer rates to ensure good yields of this high-market value crop. This chapter evaluates the performance of SUBSTOR-Potato by comparing predictions of yield and nitrate leaching with values measured by Sexton (1993) in 1991 and 1992 at Staples, MN. In this chapter, I describe the types of inputs and outputs used in the model, as well as the relationships between simulated and measured values. I also outline a procedure that could be used to evaluate the impact of climate variability on irrigation management.

At the next level of research I attempted to evaluate the relative importance of different water transport processes in the soil at Staples, MN (Chapter 3), since it is water that moves nitrate to ground water. The main objective of this research was to evaluate whether water movement was uniform and adhered to the processes implicitly contained in the SUBSTOR-Potato model (uniform, piston flow), or whether water followed preferential flow paths, bypassing portions of the soil matrix and moving more quickly to the water table. Observations of preferential movement have been increasingly reported in the literature, and several different preferential transport mechanisms have been demonstrated. To meet this objective, a field study was conducted in which a blue food dye was used as a tracer of water flow paths under different application methods and different initial soil water contents. The field plots were excavated and the dye paths examined and recorded. An evaluation was conducted in order to determine the initiating mechanism for any preferential flow paths observed. This chapter describes the patterns observed with respect to the experimental treatments, and summarizes the relative prevalence of several preferential flow path initiating mechanisms in this sandy glacial outwash-derived soil.

The third level of research (Chapter 3) explored the more basic scientific question of how the blue dye FD&C Blue #1 that was used in the field project interact with the soil. This dye has only been recently used as a tracer of water movement in soils. It is non-toxic (it is a food dye), and has good contrast with most soil colors, and therefore is likely to be chosen frequently in the future. This chapter includes comparisons of the extent of dye adsorption in our soil with recently published work by other researchers. It also examines how the various application rates used in the field likely affected the amount of adsorption and therefore the resulting dye patterns observed in the field experiment. Several issues are explored which emphasize the difficulties encountered when making interpretations of dye flow pathways, and caution are given for researchers who use dyes to trace water transport pathways to consider these factors when interpreting dye patterns in the field.

REFERENCES

Klaseus, T.G., C.G., Buzicky, and E.C. Schneider. 1988. Pesticides and groundwater: Survey of selected Minnesota wells. Report for the Legislative Commission on Minnesota Resources. Minnesota Department of Health and Minnesota Department of Agriculture.

Myette, C. F. 1984. Ground-Water-Quality appraisal of sand-plain aquifer in Hubbard, Morrison, Otter Tail and Wadena counties, Minnesota. USGS, Water Resources Investigation Report 84-4080,
p. 49.

Sexton, B.T. 1993. Influence of nitrogen and irrigation management on corn and potato response and nitrate leaching, M.S. Thesis, University of Minnesota, St. Paul., MN

CHAPTER 1. Evaluation of SUBSTOR-Potato for predicting potato yield and nitrate leaching in Minnesota outwash soils.

ABSTRACT

An evaluation of the potato growth / nitrate leaching simulation model SUBSTOR-Potato was conducted by comparing measured field data with simulated values for 1991 and 1992 (16 combinations of management and climate) in a sandy outwash soil of central Minnesota. Comparisons of measured and predicted potato yields are within the range of comparisons observed in other validation studies of SUBSTOR-Potato. Also, the predicted potato yield, N uptake, and nitrate-N leaching follow the measured trends of increases as the N application rate is increased. However, in most cases the predicted values are not within one standard deviation of the measured data.

Evaluation of the effect of changing the irrigation trigger level on yield and nitrate leaching suggests that use of a trigger level of 30 to 40% results in the best combination of relatively high yields accompanied by relatively low nitrate leaching. Probability analyses with eight years of weather data suggest that yield is greatly affected by climatic variability, and that there is little overlap in the yield ranges resulting from different application rates except at the highest N rates evaluated. Nitrate leaching was affected only slightly by climatic variation, and there was little difference in the amount of leaching incurred under the different N application rates except for three of the eight years. These analyses also support the pattern observed above of higher yields and lower nitrate leaching when using an irrigation trigger level of 40 rather than 60%. The probability analyses in this paper used only a eight years of weather data, and therefore it is not advised that management decisions be made based solely on these results. Instead these analyses provide an outline that could be followed for using the model to make management decisions. Overall SUBSTOR-Potato appears useful for qualitative predictions, however there are several reasons for urging caution when making quantitative interpretation of the data.

INTRODUCTION

Conditions which promote nitrate leaching include high nitrogen additions to the soil, high water inputs, and permeable soils. All of these factors are present in commercial potato production in central Minnesota. Soils used for irrigated potato production in this region are primarily developed in sandy outwash plains. These highly permeable soils coupled with potatoes' shallow rooting systems and sensitivity to moisture stress necessitate high water inputs through irrigation to ensure a productive crop. Potatoes also require large amounts of nitrogen to be profitable. Fertilizer and irrigation additions are relatively cheap in comparison to the potential market value of the crop. As a result of the high cash value of this crop, growers often over-apply irrigation water and nitrogen as insurance against yield reductions due to water or nitrogen stress. All of these factors suggest that potato production may contribute to nitrate contamination of groundwater in this region. A USGS study of 124 wells in Hubbard, Morrison, Otter Tail and Wadena counties in central Minnesota showed that nitrate and nitrite concentration have been continuously increasing since 1960's (Myette, 1984). In some wells, concentration of nitrate and nitrite have exceeded the EPA drinking water standards of 10 ppm. A 1988 survey of 500 shallow observation wells and drinking water wells in 51 counties of Minnesota by Klaseus et al. (1988) found that 33% of the examined wells contained elevated levels of nitrates. A significant number of these wells were in the Central (Sand Plain) region of the state.

Evaluating the potential for a compound such as nitrate to leach through soil to groundwater is expensive and time-consuming because of the many soil-climate-management combinations which exist. An alternative to numerous field assessments of nitrate leaching is the use of validated computer simulation models. Once validated for a site, such a model can be a powerful tool for predicting nitrate leaching under a variety of different management scenarios. Comparison of the long term leaching potential under different management scenarios can aid in the development of practices that minimize potential leaching while maintaining profitable yields.

There are several existing models that predict nitrate leaching in soils, including LEACHM (Hutson and Wagenet, 1989), NCSOIL (Molina et al., 1983), NLEAP (Shaffer et al., 1991), and RZWQM (USDA-ARS 1992), as well as models that predict potato growth (Iritani, 1963; Manrique and Bartholomew, 1991; Ingram and McCloud, 1984; Ng and Loomis, 1984). However none of these models predict both growth and leaching. SUBSTOR-Potato (SUBsurface STORage organ), developed as one of the IBSNAT (*International Benchmark Sites Network for Agrotechnology Transfer*) family of crop models, is a simulation model of both potato development and nitrate leaching. Other members of the IBSNAT family include the well-known CERES group of models (e.g., CERES-Maize, CERES-Wheat). The SUBSTOR-Potato model is relatively new and has undergone limited testing. The only published evaluation was conducted by researchers associated with development of the model (Griffin et al., 1993), and this study did not include any locations that have the climatic conditions of Minnesota. However, the model does contain many of the same modules found in the extensively-tested CERES models, for example the water balance and N transformation routines.

The model uses inputs of soil properties, climatic data, irrigation and fertilizer additions, previous crop residue, and several other management considerations to simulate yield and nitrate leaching. In addition to predicting yield and nitrate leaching, model outputs also include water and nitrogen balance components, and plant development over the season. The model runs on a daily time step. Model calculations are based primarily on experimental relationships reported in the soil science and potato literature. In general, most processes are calculated by first determining the maximum rate possible and then decreasing this rate if non-optimal conditions of soil water, soil temperature, or soil nitrogen exist.

The objectives of this study were to evaluate the SUBSTOR-Potato model's ability to predict potato yield and nitrate leaching in sandy outwash soils of central Minnesota, and to use the model with historic weather data to identify management practices that can minimize nitrate leaching without significantly affecting crop yield. To meet the first objective, simulation results were compared with measured data collected for 16 treatment-years by Sexton (1993). To meet the second objective, simulations were made using historic weather data to evaluate ranges in yields and nitrate-N leaching as a function of climate variability.

METHODS

Model Evaluation

The model evaluation consisted of comparing simulated potato yield and nitrate leaching with measured field data taken during 1991 and 1992 for several combinations of nitrogen fertilization and irrigation management practices on Verndale sandy loam (coarse loamy over sandy, mixed, frigid, Udic Argiborolls) near Staples, Minnesota. The field data used were taken from Sexton (1993). These two years of experimental data provide a total of 16 different management-soil-climate combinations that can be used in the evaluation. All simulations were conducted using a version of SUBSTOR-Potato that contains the N transformation modifications suggested by Vigil et al. (1991).

Field Measurements

Details of the Staples field experiments used in the validation are given in Sexton (1993). An outline of the field experiment is given in Table 1-1. Briefly, the treatments included four rates of commercial ammonium nitrate fertilizer and two irrigation schedules, both during 1991 and 1992. Irrigation Schedule #1 was a fixed rate of application, representing "typical" irrigation management in the area. Irrigation Schedule #2 was a "conservation" management system, in which irrigation amounts were varied according to crop growth stage in order to minimize leaching of water below the root zone. Irrigation additions for both schedules were determined using the checkbook method (Wright and Bergsrud, 1986). Irrigation schedule #1 consisted of water applications when 25% (1991) or 32% (1992) of the soil available water holding capacity was depleted by evapotranspiration. That is, available water is depleted to 75% of the soil's total available water-holding capacity. Irrigation schedule #2 allowed the soil to get slightly drier before water application. The depletion when irrigation was applied in schedule #2 depended on plant growth stage. In 1991 these depletions were 50% or 30% (depending on plant stage), while in 1992 these depletions were 50% or 40%.

Nitrate concentrations in the soil water below the root zone were determined from soil water samples taken from suction cup samplers. The total amount of N leached below the root zone (kg ha^{-1}) was calculated by multiplying the nitrate N concentrations by the flux of water past the root zone (percolation). In 1991, water flux (percolation) was estimated using a mass balance approach, that is:

$$\text{PERCOLATION} = \text{RAIN} + \text{IRRIGATION} - \text{EVAPOTRANSPIRATION} \qquad \textbf{(1-1)}$$

Evapotranspiration was estimated using the checkbook method of Wright and Bergsrud (1986) which requires air temperature and crop growth stage. In 1992, percolation was calculated with Darcy's law, using measured soil hydraulic gradient (measured with tensiometers) and the corresponding soil hydraulic conductivity. Tuber biomass and N content were measured at harvest. Vine plus leaf biomass and N content were measured just before vine-kill.

Input data

Irrigation inputs to the model consisted of the amount and timing of water applications. During the validation portion of this study irrigation was set to 'field schedule' in the management input file (FILE 8) to allow the use of actual experimental rates and timings.

For simulations conducted with historic weather data, this setting was changed to allow the model to add irrigation when the soil water content was decreased below a specified irrigation trigger level. The 'trigger level' is a user-specified input (THETAC) and refers to the proportion of the total available water-holding capacity that the soil can be depleted to before irrigation is added. An irrigation trigger level of 40% means that irrigation water will be applied when the available water in the soil decreases to just below 40% of available water holding capacity.

Fertilizer inputs were the amount and timing of N additions, plus the depth of incorporation. Total amounts of irrigation and fertilizer are given in Table 1-1. In addition to ammonium nitrate fertilizer, there was some additional native nitrogen in the irrigation water (approximately 6 mg L^{-1}). This was equivalent to an addition of about 8 kg N ha^{-1} in 1991 and 17 kg ha^{-1} in 1992. This N was added to the fertilization input file on the dates of irrigation. The values given for N application rates throughout the rest of this manuscript include both fertilizer and irrigation-water N additions.

For the 1991 season, the previous crop at this site (i.e., in 1990) was non-irrigated corn (*Zea mays* L.). Stover biomass was not measured in that year, therefore inputs of previous crop residues for 1991 were estimated from an estimated yield of non-irrigated corn for the area (60-70 bu ac^{-1}). A grain-to-stover ratio of 1:1 was used to estimate stover biomass of 3443 kg ha^{-1} at harvest (Lindstrom et al., 1981). This value was multiplied by 0.8 to account for residue decay over winter. The C/N ratio of the corn residue was estimated to be 60. Previous crop root biomass of 970 kg ha^{-1} was determined by assuming the roots comprised 15% of the total biomass ([grain+stover]/0.85) and then multiplying this by 0.8 to account for decay over winter. These values for residue and root biomass were used for all treatments in 1991. For the 1992 season, previous crop residue and C/N ratio were taken from the 1991 measurements of Sexton (1993) for each treatment. Previous crop root biomass was estimated for each treatment using the same procedure as in 1991. Values used for the previous crop residue and root biomass used in the simulations are given in Table 1-2.

Soil properties and general climate information used in the simulations are given in Table 1-3. These values were used for all simulations in both years. The soil layers delineated for the model input were based on soil horizon thickness. The one exception was the 25 cm thick Ap horizon, which was split into two layers to meet the authors' suggestion that the surface layer thickness be no greater than 15 cm. Measured soil properties include bulk density, organic carbon and pH (Table 1-3), and initial soil NH_4^+ and NO_3^- (Table 1-4). The drained upper limit water content (DUL) and lower limit of plant-extractable water (LL) were estimated from laboratory measurements of water content at -1 and -1.5 MPa respectively. Saturated water content was estimated as

$$SAT = 1 - (\text{Bulk Density}/2.65) \qquad (2)$$

The root weighting factor (WR) was calculated following the method of Jones and Kiniry (1986). The initial water content was set at the DUL water content for each layer (Table 1-3). Annual mean air temperature and monthly amplitude in air temperature were taken from the Wadena County (Minnesota) Soil Survey and represent the 30-year (1951-1980) normal. The values used for bare soil albedo, upper limit of stage 1 evaporation, and SWCON (soil water drainage term) were determined based on procedures suggested by Ritchie and Crum (1989).

Seed potato pieces were planted in rows 0.91 meters apart. Seed pieces were 15 cm deep at 25 cm spacing, resulting in a plant population of 4.78 plants per m^2. Reserve seed carbohydrate was estimated to be 17 g by assuming carbohydrates comprised 20% of the fresh weight of 85 g seed pieces and sprout length at planting was assumed to be zero. Observed dates of 50% emergence were input for both years (May 30, 1991 and June 8, 1992).

For both 1991 and 1992 the potato cultivar was Russet Burbank. The values used for the genetic coefficients for this cultivar (Table 1-5) were the values contained in the "Genetics Input File" (FILE9) included on the distribution diskette (i.e., we did not change any of these coefficients).

Simulations were run for all four nitrogen application rates and two irrigation schedules in each year. The depth of the soil profile used in each simulation was set to match the depth of the suction samplers used in the field experiment to measure nitrate concentration in percolating water (61 cm in 1991 and 91 cm in 1992). Comparisons of simulation results with the measured data (percolation, evaporation, nitrate leaching) were made only for the periods over which measurements were taken. The dates over which these measurements were taken are listed in Table 1-6.

The typical management practice in the field for this region is to kill the vines a few weeks before harvest in order to 'set' the skins of the potatoes. The model on the other hand does not provide for vinekill. Therefore values used as simulation results for plant yield and N leaching were the values that occurred on the same date as vine kill (September 12) in 1991. In 1992, the field crop succumbed to potato blight during the period of linear tuber bulking. Since SUBSTOR-Potato does not have mechanisms to account for disease effects, simulated yield, N uptake and N leaching were taken on the day when the field was at 50% senescence (August 21). Embedded in this approach is the assumption that there was no change in tuber biomass between 50% senescence and harvest.

Impact of climate variability

In addition to validation runs, simulations were also run to assess the impact of climate variability on predicted potato yield, N uptake and N leaching. Only ten years (1981-1988, 1991, and 1992) could be used for this exercise due to limitations on obtaining long term climate data in this area. The closest site to Staples, MN where solar radiation records were available was Fargo, ND, and the only records easily accessible were 1981-1988. The daily minimum and maximum temperatures and precipitation were measured at Wadena, MN. Other soil and management inputs used in these simulations were same as for the Staples 1991 simulations.

Climate variability simulations were made using the model option that allows the model to add irrigation water when the soil water is depleted to a user-specified amount. In order to determine the most appropriate trigger level to be used in examining the effect of climate variability, simulations were run to assess the effect of various irrigation trigger levels on crop yield, N uptake, and N leaching using the soil, crop, and management inputs for 1991 and 1992, using the highest rate of N fertilizer (277 kg ha^{-1}). The irrigation trigger levels tested were: 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. Based on this analysis (see *Results and Discussion* section), simulations were then run with the historic weather data using trigger levels of 40 and 60 percent.

RESULTS AND DISCUSSION

Model Evaluation

Comparisons of the predicted and measured potato yield, tuber N uptake, and N leaching for the two irrigation schedules and four fertilizer treatments for 1991 and 1992 are given in Figs. 1 and 2. In all cases, the simulated yields, N uptake, and nitrate-N leaching followed the patterns of the field measurements, i.e. yield, N uptake, and nitrate-N leaching all increasing with increasing N application rate. However, yield and N uptake predictions are generally not within one standard deviation of the measured values. (Standard deviations of N leaching in the field were not compiled by Sexton, 1993). In both years, the simulated potato yields are lower than the measured values. The relationship between measured and predicted yields in our study fall within the range of variability seen in similar comparisons (Fig. 1-3) conducted by Griffin et al. (1993), although our values are all below the 1:1 line.

The differences in predicted yield between the two irrigation schedules are small (Figs. 1 and 2). In 1991, differences between measured and predicted yield are largest for the control treatments (Fig. 1-1), whereas in 1992 (Fig. 1-2) the differences were largest for the highest commercial N treatments (197 and 286 kg N ha^{-1}). Predicted tuber N uptake is close to the measured values for 1991, in spite of the lower predicted yield. This is because predictions of tuber N concentrations were higher than measured (data not shown). Predicted N uptake in 1992 is lower than the measured values. Predicted N leaching is lower in 1991 and higher in 1992 than the measured values. Differences between the predicted and measured N leaching are greater for higher N application rate.

The 1992 comparisons are somewhat more difficult because the potatoes in the field succumbed to early blight (*Alternaria solani*), and died several weeks before the end of the season. SUBSTOR-Potato does not incorporate the effects of disease and other pests (e.g., weeds, insects) on potato growth. This is one of the limitations of the model. The model assumes that these effects are taken care of through management. In order to estimate the model's performance in 1992, comparisons were made between measured data at harvest (yield, N uptake) and model predictions on August 21 (instead of the date of maturity) which is the date of 50% senescence observed in the field. This approach implicitly assumes that there was no growth between 50% senescence and harvest.

The relatively lower agreement between measured and predicted yield at the low N application rates in 1991 suggests that there was extra N available in the field system that is not accounted for in the model inputs. In other words, the high measured yields at low N application rates may be due to the presence of unaccounted-for N in the field, which becomes less important at higher N application rates. One possible source of such N is legumes (lupines) that were on this site two years earlier. Lupines have a low carbon-to-nitrogen ratio (C/N ratio) and can contribute N to the following crop. A sensitivity analysis of the model to residue C/N ratio input (Fig. 1-4) shows that the model is only slightly sensitive to C/N ratio, unless it is below about 20. Other possible explanations for the divergence between measured and predicted yields at the lower N rates include poor estimates of the amount of residue remaining from the previous year, or poor mineralization predictions by the model.

Sensitivity Analysis of Irrigation Trigger Level

The effects of various irrigation trigger levels on potato yields, N leaching, irrigation amount, and on the water and N stress factors predicted by SUBSTOR-Potato for 1991 and 1992 management conditions are plotted in Figs. 5 and 6. At trigger levels above 10%, potato yields are reasonably similar for all irrigation trigger levels. As the irrigation trigger level increases, nitrate-N leaching, irrigation amount added, and N stress factor all increase whereas the water stress factor decreases. (The high N leaching observed at 0% trigger in 1991 is likely due to the very low yield.) The increase in the N stress factor with an increase in irrigation trigger level is due to larger total irrigation amounts and consequently higher N leaching at the higher trigger levels. The simulation results suggest that irrigation trigger levels below about 30 to 40% subjected the plants to water stress, while increasing the level above 30 to 40% increased the amount of N stress the plant experienced. In general, trigger levels around 30 to 40% resulted in relatively high yields and low N leaching for this treatment (277 kg ha^{-1} N applied).

One anomaly seen during this sensitivity analysis was the very high N leaching occurring with 50% trigger level in 1991 (Fig 5). This anomaly was investigated by plotting the daily inputs of precipitation and irrigation and outputs of water drainage and N leached (Figs. 7, 8, and 9). Comparison of Figs. 7, 8, and 9 shows that higher leaching at 50% trigger is the result of irrigation immediately preceding a series of relatively large precipitation events. At 40% irrigation trigger level, there was no irrigation applied before day of year (DOY) 199 and therefore all N leaching between DOY 181 and 189 is due only to excess rain water. At 50% irrigation trigger level on the other hand, 48 mm irrigation water was added on DOY 171. This addition, in conjunction with the three subsequent major precipitation events, led to higher drainage and thus higher N leaching. At 60% irrigation trigger level, irrigation was applied on DOY 168, and was a slightly lower amount than applied with 50% irrigation trigger. As a result, less N leaching occurred compared to the 50% irrigation trigger level.

The above analysis shows that occurrence of precipitation is a major factor in controlling N leaching even if a best irrigation management practice of not irrigating to water contents greater than field capacity is followed. This suggests that the best strategy for minimizing N leaching in Minnesota outwash soils of low water-holding capacity is to leave some unfilled pore space in soils to capture rain-water that could potentially arrive soon after irrigating. In other words, it is suggested that irrigation occur only to some level below field capacity (for example to 90% of field capacity).

Impact of Climate Variability

Patterns in yield and nitrate-N leaching

Cumulative probabilities of potato yield and N leaching for the four N treatments and two trigger levels, using weather data from 1981, 1984-1988, and 1991 and 1992 are shown in Figs. 10 and 11. (Weather data from 1982 and 1983 were not used due to problems with the simulations for these years, which are discussed in the following section). Irrigation trigger levels of 40% and 60% were chosen for the climate variability simulations since these were the levels used by Sexton (1993) for irrigation management and follow the irrigation strategy suggested by Wright and Bergsrud (1986).

Variation in climatic conditions for these eight years caused variations in yield of 50 to 100% for a given N treatment. Distinct differences in yield are seen between the control, 98, and 188 kg ha^{-1} N curves. Differences in yield between the two highest N rates are lower, and in fact show that variations in climate cause the range in yield to overlap in the 30 to 40 Mg ha^{-1} portion of the graph. Slightly higher yields resulted from use of 40% compared to 60% irrigation trigger deficit for all treatments.

Cumulative probabilities of N leaching at the two trigger deficits show that with the exception of the control treatments, there is little difference in N leaching between the various N application rates evaluated. The differences that occur are in the extreme events, i.e., the three highest leaching years of the eight evaluated. There is almost no relationship between the yield for a given treatment and year, and the corresponding amount of N leaching predicted (Fig. 1-12). Calculated correlation coefficients (r^2) were very low (0.02 and 0.04 respectively for the predictions from 40 and 60% trigger levels). The only pattern observed occurred with the 1985 weather data, the year of highest N leaching (the six major outliers in Fig. 1-12).

Overall, N leaching was slightly higher with 60% trigger levels compared to 40%. This is seen both in simulations that varied the irrigation trigger level for 1991 and 1992 management conditions (Figs. 1-5 and 1-6) and in the values at cumulative probabilities of 0.5 calculated from the eight years weather data. This conclusion is based on only a few years of data (just two in the first case and only eight in the second), and could be more rigorously evaluated if a longer weather record were used (e.g., 30 or more years). At this time, we do not necessarily recommend that management decisions be based on this analysis, but instead present this as an example outlining the types of analyses that could be done with this model. We strongly encourage the use of longer weather records for making these kinds of management decisions.

Explanation of problems with 1982 and 1983 simulations
The original simulations using 1982 and 1983 weather data resulted in zero potato yield. During these two years, the model never allowed the plants to develop tubers. Initially it was suggested that this was due to low moisture conditions in the seed zone, despite there being enough water in the entire profile so irrigation was not triggered (J.T. Ritchie, personal communication, 1993). This turned out not to be the problem. Instead we have since found that the lack of tuber growth was due to a logical problem in the model that occurred from a seemingly unique set of low temperatures following germination such that the growth routines were not activated properly. We found that we could overcome this problem by not inputting an observed emergence date and instead rely on model calculations of emergence which are based on temperature inputs (results not shown). With hindsight it appears appropriate to use on the model calculations rather than observed dates, however our use of observed emergence dates was based on the recommendations of the model developers (Griffin et al., 1993) who strongly suggest using observed emergence dates. All simulation results presented in this paper used observed emergence dates for the management year used (i.e., 1991 or 1992), and we did not have the opportunity to go back and rerun the probability analyses to include the 1982 and 1983 data.

SUMMARY AND CONCLUSIONS

Comparisons of measured and predicted potato yields are within the range of comparisons observed in other validation studies of SUBSTOR-Potato. Also, the predicted potato yield, N uptake, and nitrate-N leaching follow the measured trends of increases with increased N application. However, in most cases the predicted yield and N uptake are not within one standard deviation of the measured values.

Sensitivity analyses with 1991 and 1992 weather and management inputs as well as probability analyses suggest that lower trigger levels (30 to 40%) are better than higher levels (60%) for maintaining good yields while keeping nitrate leaching relatively low. Probability analysis also showed that except for the control treatments, the amount of N leaching was nearly the same for all N application rates, and that there was little variation in the amount of N leaching as a function of climate except for some extreme years. In those extreme years, the amount of N leaching increased with increased N application rate.

Overall, the evaluation of the model found that measured and predicted values followed similar trends and, it appears that SUBSTOR-Potato is at least able to provide qualitative predictions. However several problems were observed during this study, which urge caution if making quantitative interpretation of the data. These 'problem areas' are fertile ground for future research - and further work to improve them will make the model generally more reliable, and also cause us to come to a better understanding of the interrelationships within a very complex system involving physical, chemical, biological, and climatological interactions.

FUTURE RESEARCH

Our work to evaluate this model has provided us with several ideas for additional work, including consideration of a two-dimensional approach for modeling the flow of water and nutrients, especially early in the season when roots do not extend out of the rows.

Several gaps in present knowledge of potato production in Minnesota were also found, suggesting several areas for future field research. These include evaluation of the effect of different irrigation trigger levels on yield and N leaching in field experiments, determination of the N rate at which there is little further increase in yield; determination of the amount of N mineralized from Minnesota outwash soils for a variety of residue types and amounts, and determination of potato growth over the season for a variety of different treatments, particularly mobilization of N from the leaves to the tubers near the end of the season.

Ideally for management purposes, a careful evaluation of the plant-growth part of the model would be beneficial for understanding the interacting effects of soil, management, and climate on potato growth and yield. Such an evaluation could be done by comparing patterns in root, vine, and tuber growth with measured field data on these variables. Detailed plant growth data has been collected by Dr. Carl Rosen's group (among others) for several cropping years, and provide an excellent means for evaluating these aspects of the model.

REFERENCES

Griffin, T.S., B. S. Johnson, and J.T. Ritchie. 1993. IBSNAT Research Report Series 02. A simulation model for potato growth and development: SUBSTOR-Potato version 2.. Dept. of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, Univ. of Hawaii, Honolulu, HI.

Hutson, J.L. and R.J. Wagenet. 1989. LEACHM-Leaching Estimation and Chemistry Model. ver. 2. Department of Agronomy. Cornell University, Ithaca, N.Y..

Ingram, K.T. and D.E. McCloud. 1984. Simulation of potato crop growth and development. Crop Sci. 24:21-27.

Iritani, W. M. 1963. The effect of summer temperature in Idaho on yield of Russet Burbank potatoes. Amer. Potato J. 40: 47-52.

Klaseus, T.G., C.G., Buzicky, and E.C. Schneider. 1988. Pesticides and groundwater: Survey of selected Minnesota wells. Report for the Legislative Commission on Minnesota Resources. Minnesota Department of Health and Minnesota Department of Agriculture.

Manrique, L. A. and D. P. Bartholomew. 1991. Growth and yield performance of potato grown at three elevations in Hawaii. II. Dry matter production and efficiency of partitioning. Crop Sci. 31: 367-372.

Molina, J.A.E., C.E. Clapp, M.J. Shaffer, F.W. Chichester, and W.E. Larson. 1983. NCSOIL, a model of nitrogen and carbon transformations in soil: description, calibration, and behavior. Soil Sci. Soc. Am. J. 47:85-91.

Myette, C. F. 1984. Ground-Water-Quality appraisal of sand-plain aquifer in Hubbard, Morrison, Otter Tail and Wadena counties, Minnesota. USGS, Water Resources Investigation Report 84-4080,
p. 49.

Ritchie, J.T. and J. Crum. 1989. Converting soil survey characterization data into IBSNAT crop model input. In: J. Bouma and A.K. Bregt (eds): Land qualities in space and time. Wageningen, the Netherlands, pp. 155-167.

Sexton, B.T. 1993. Influence of nitrogen and irrigation management on corn and potato response and nitrate leaching, M.S. Thesis, University of Minnesota, St. Paul., MN

Shaffer, M.J., A.D. Halvorson, and F.J. Pierce. 1991. Nitrate leaching and economic analysis package (NLEAP): Model description and Application in Follett, R.F., D.R. Keeney, and R.M. Cruse. eds. Managing nitrogen for groundwater quality and farm profitability. Soil Science Society of America, Inc., Madison, Wisconsin.

USDA-ARS. 1992. Root zone water quality model. Great Plains Systems Research Technical Report No. 2. p. 236.

Vigil, M.F., D.E. Kissel, and S.J., Smith. 1991. Field crop recovery and modeling of nitrogen mineralized from labeled sorghum residues. Soil Sci. Soc. Am. J. 55:1031-1037.

Wright, J., and F.Bergsrud. 1986. Irrigation scheduling - Checkbook method. Publ. AG-F9-1332. Minnesota Ext. Serv. Univ. of Minnesota, St. Paul.

Table 1-1. Field Experiment Design 1991 and 1992, Staples, MN.

Location:	Staples Irrigation Center, Staples, MN
Soil Type:	Verndale sandy loam (coarse loamy over sandy, mixed, frigid Udic Argiborolls)
Land Slope:	< 2%
Potato Variety:	Russet Burbank.
Climate Data:	Measured on Site (precipitation, minimum and maximum temperature, solar radiation).
N Rates:	0, 90, 180, 269 kg N/ha NH_4NO_3 in 3 applications (at planting, emergence and hilling) plus N in the irrigation water.
Previous Crop:	1991: dryland corn (Plowing depth: 23cm) 1992: irrigated corn (Plowing depth: 23cm)
Irrigation:	1991: Schedule #1 - 20 cm in 11 applications Schedule #2 - 22 cm in 10 applications 1992: Schedule #1 - 23 cm in 9 applications Schedule #2 - 16 cm in 7 applications

Table 1-2. Values used for organic residues inputs from the previous crop.

	Residue (kg/ha)	Root Biomass (kg/ha)
1991		
(All treatments)	2750	970
1992		
Irrigation Schedule #1		
0 kg N/ha	5425	2056
90 kg N/ha	6270	2504
180 kg N/ha	6220	2531
269 kg N/ha	7090	2738
Irrigation Schedule #2		
0 kg N/ha	5390	2101
90 kg N/ha	5425	2257
180 kg N/ha	6140	2548
269 kg N/ha	5520	2419

Table 1-3a. Values used for whole-profile soil characteristics and general climate input variables used for all simulations at Staples, MN.

Input Variable	Value Used
Bare soil albedo:	0.09
Upper limit stage 1 evap (mm):	6.0
Fraction drained in 1 day:	0.60
SCS Runoff Curve:	62
Annual Mean Air Temperature (°C):	4.6
Annual Amplitude in Mean Monthly Air Temperature (°C):	17.8

Table 1-3b. Values used for layer-specific soil input variables† used for all simulations at Staples, MN.

Horizon	Thickness	LL	DUL	SAT	WR	BD	OC
	(cm)	---------- $cm^3\ cm^{-3}$ ----------				$Mg\ cm^{-3}$	%
A	13	0.07	0.23	0.407	1.00	1.57	1.30
	12	0.07	0.23	0.407	0.68	1.57	1.30
Bt	15	0.10	0.27	0.328	0.52	1.78	0.70
BC	13	0.07	0.23	0.407	0.39	1.57	0.50
C1	28	0.07	0.15	0.423	0.26	1.53	0.25
C2	20	0.07	0.15	0.423	0.16	1.53	0.10
	20	0.07	0.15	0.423	0.11	1.53	0.10

† L=Lower limit of plant-extractable water; DUL=Upper limit of plant-extractable water; SAT=Saturated water content; WR=Root weighting factor.; BD=Bulk density; and OC=Organic Carbon.

Table 1-4. Initial soil conditions used in simulations at Staples, MN

Horizon	Thick	SW†	NH_4	NO_3	pH
	cm	$cm^3\ cm^{-3}$	-- mg kg^{-1} soil --		
Ap	13	0.23	2.0	2.0	6.9
	12	0.23	2.0	2.0	6.9
Bt	15	0.27	2.0	2.0	6.6
BC	13	0.23	2.0	2.0	6.5
C1	28	0.15	1.0	1.0	6.5
C2	20	0.15	1.0	1.0	6.5
	20	0.15	1.0	1.0	6.5

† Initial soil water content.

Table 1-5. Genetic coefficients used in simulations (from model distribution diskette).

Variable	Value Used
Leaf Expansion Rate ($cm^2\ m^{-2}\ day^{-1}$)	2000.0
Tuber Growth Rate (g $cm^{-2}\ day^{-1}$)	22.5
Photoperiod Sensitivity	0.6
Critical Temperature for Tuber Induction (°C)	17.0

Table 1-6. Periods over which model simulation values were compared to measured values.

	1991	1992
Water percolation	May 3 to Sept. 17	May 19 to Aug. 21
Evaporation	May 27 to Sept. 17	May 28 to Aug. 21
Nitrate-N leaching	May 3 to Sept. 17	May 19 to Aug. 21

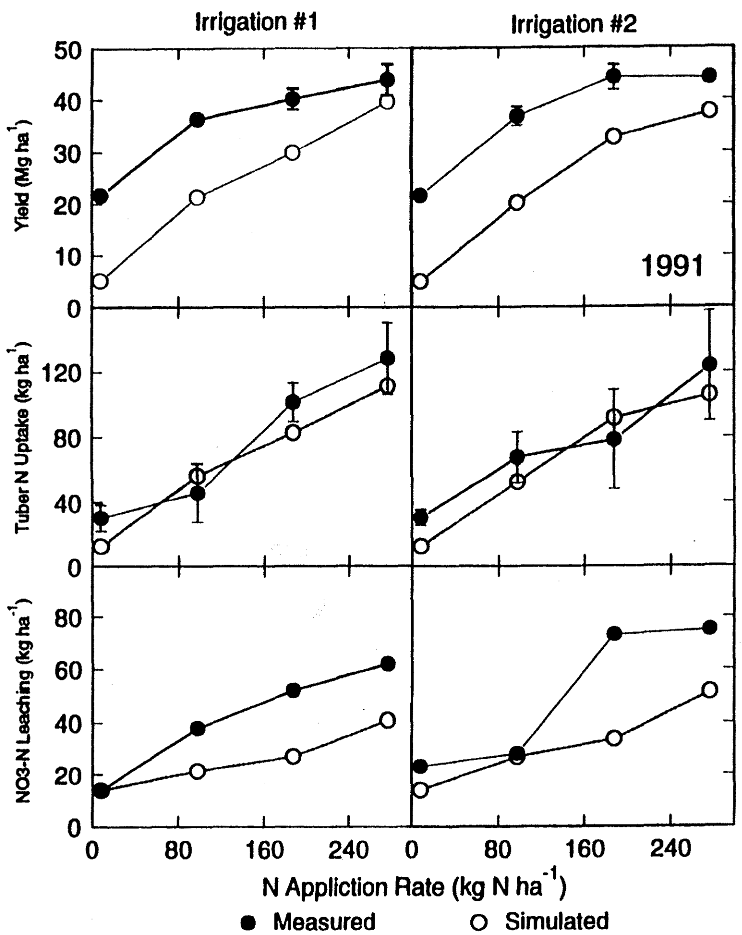


Fig. 1-1. Comparison of measured and simulated yield, tuber N uptake, and nitrate-N leaching for various N application rates at Staples, MN during 1991.

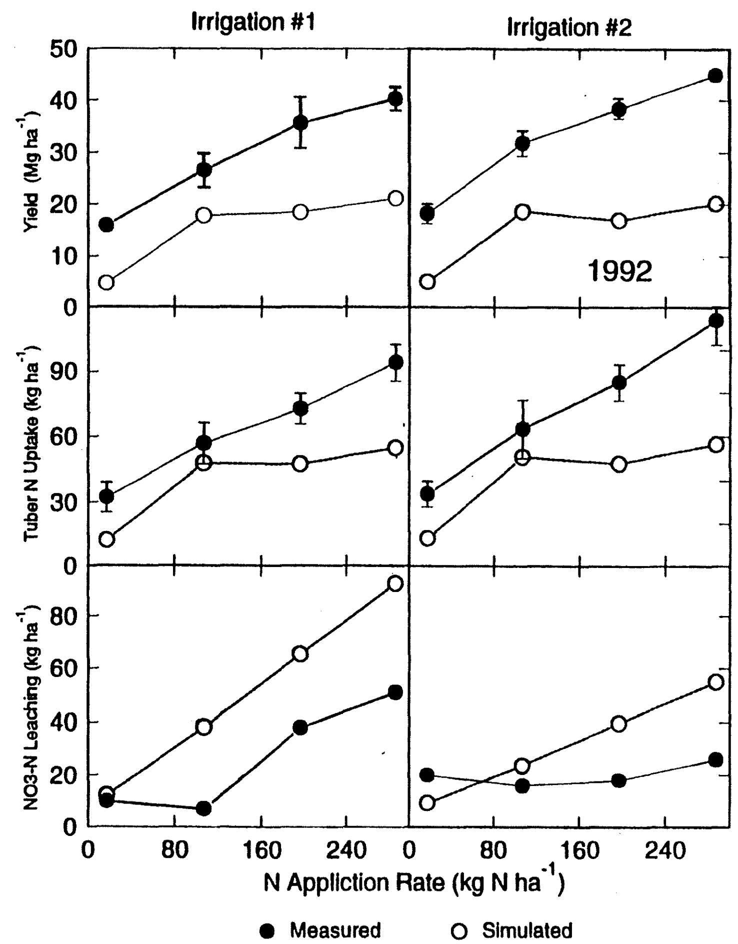


Fig. 1-2. Comparison of measured and simulated yield, tuber N uptake, and nitrate-N leaching for various N application rates at Staples, MN during 1992.

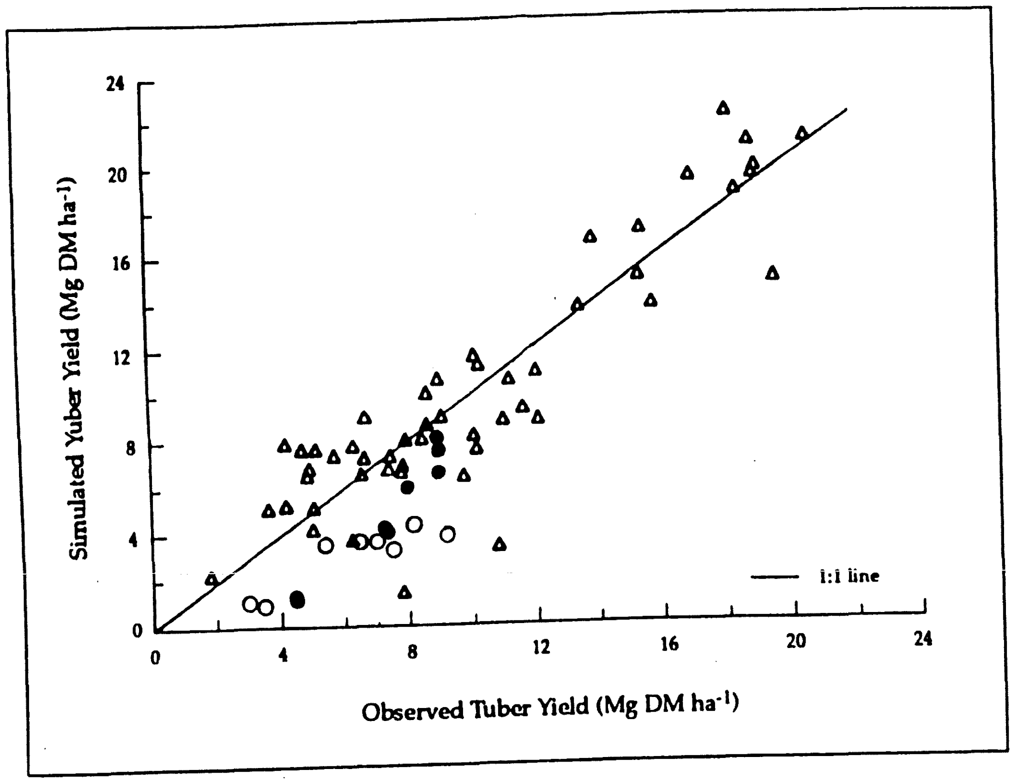


Fig. 1-3. A comparison of simulated *vs.* measured yield of potatoes (dry weight basis). The original figure is taken from Griffin et al. (1993) showing the results of their evaluation (Δ), with the addition of the results of this study in 1991 (●) and 1992 (○).

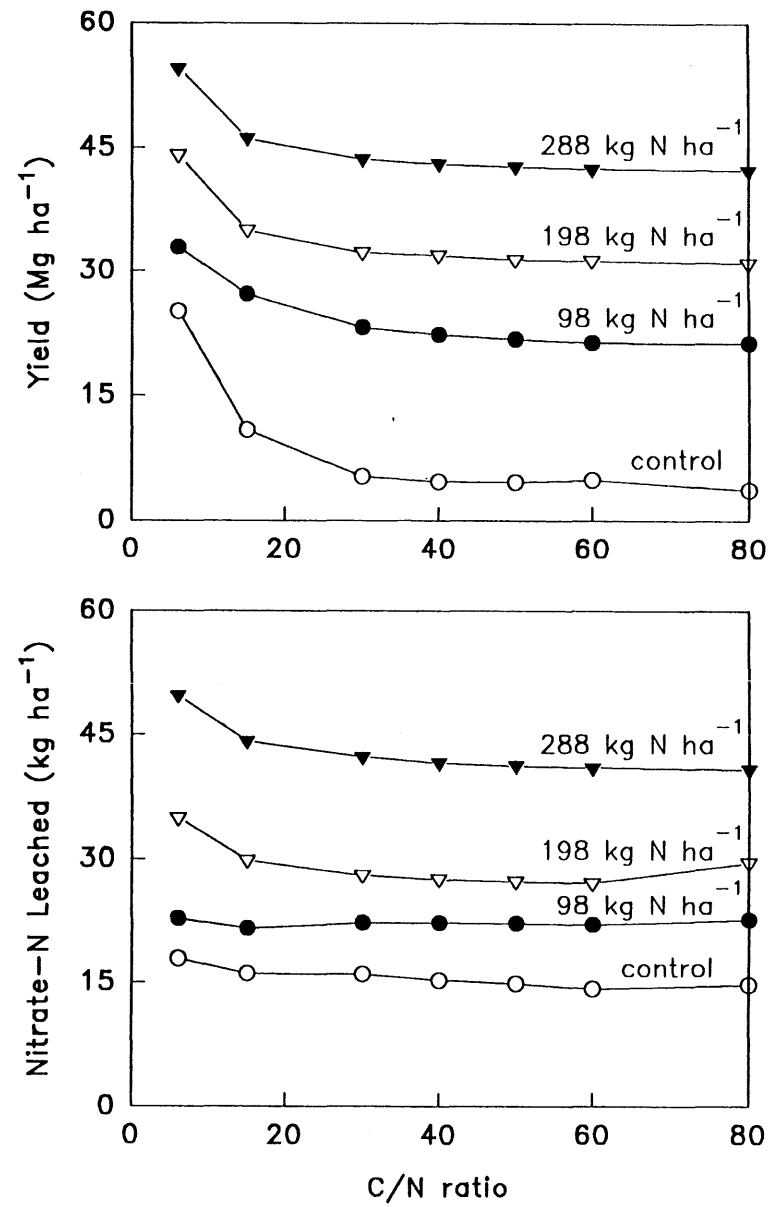


Fig. 1-4. Sensitivity analysis of predicted yield and nitrate-N lea[illegible]g to C/n ratio of the previous crop residue at various N application [illegible]

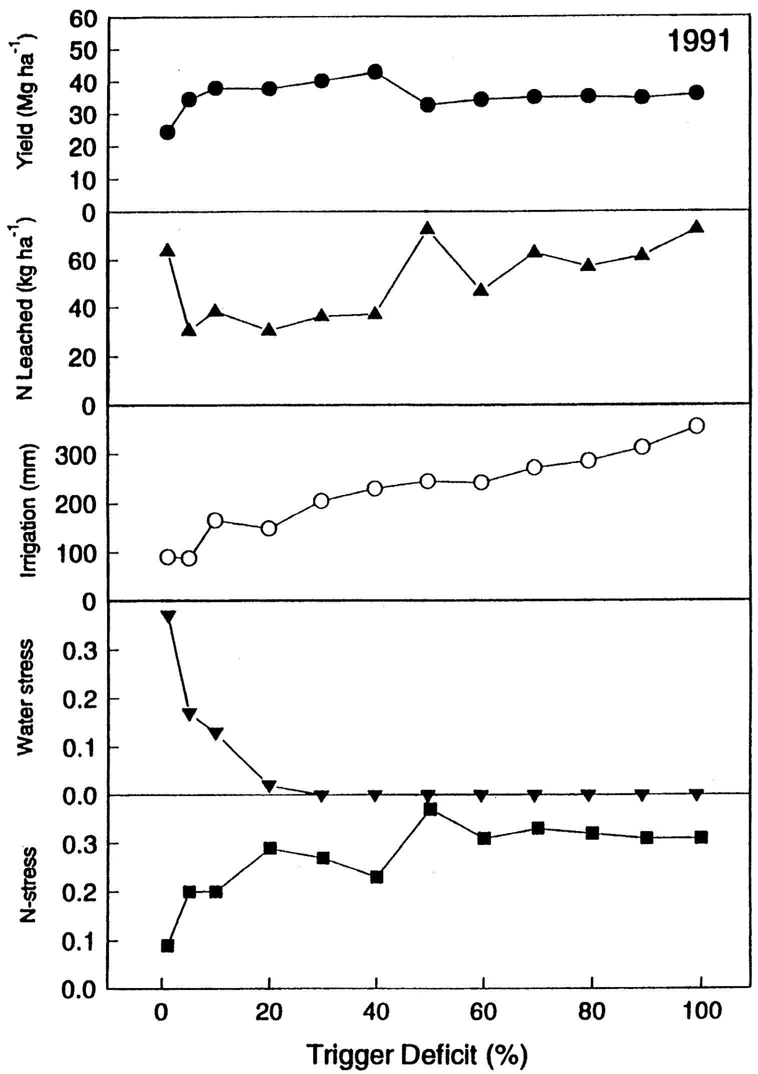


Fig. 1-5. Effects of irrigation trigger level (percent of extractable water remaining in soil before irrigation) on potato yield, nitrate-N leached, amount of irrigation added, and water and N stress under conditions of high N fertilizer (277 kg ha^{-1}) during 1991 at Staples, MN.

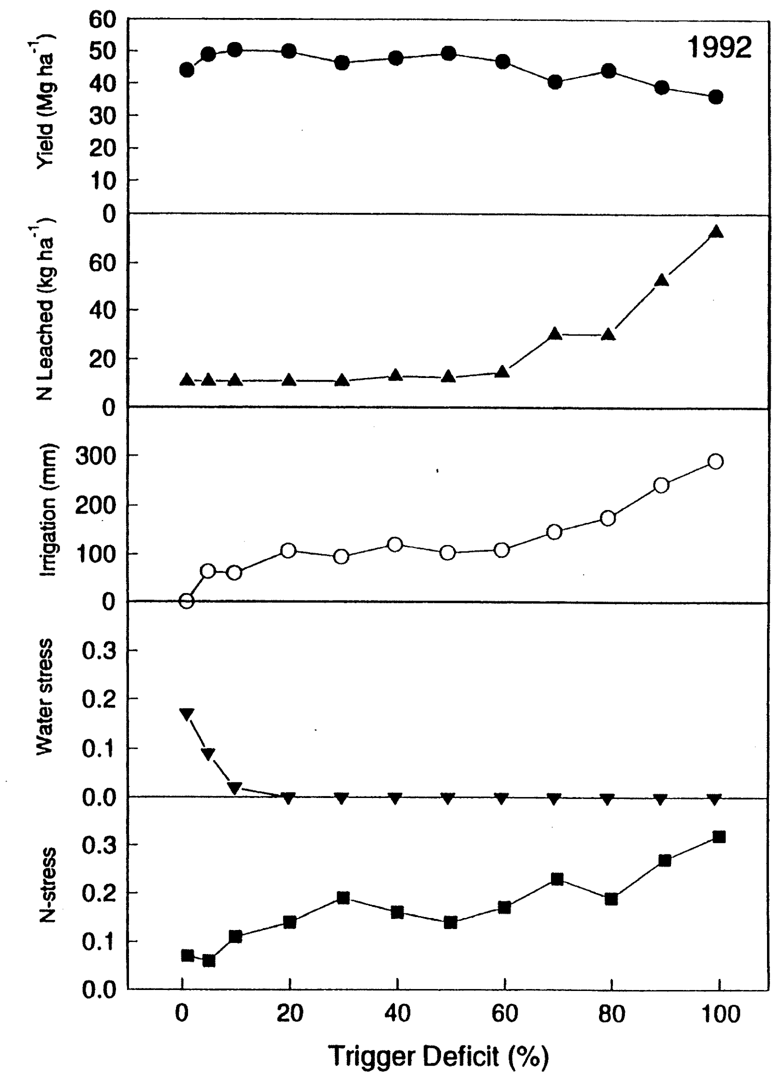


Fig. 1-6. Effects of irrigation trigger level (percent of extractable water remaining in soil before irrigation) on potato yield, nitrate-N leached, amount of irrigation added, and water and N stress under conditions of high N fertilizer (277 kg ha^{-1}) during 1992 at Staples, MN.

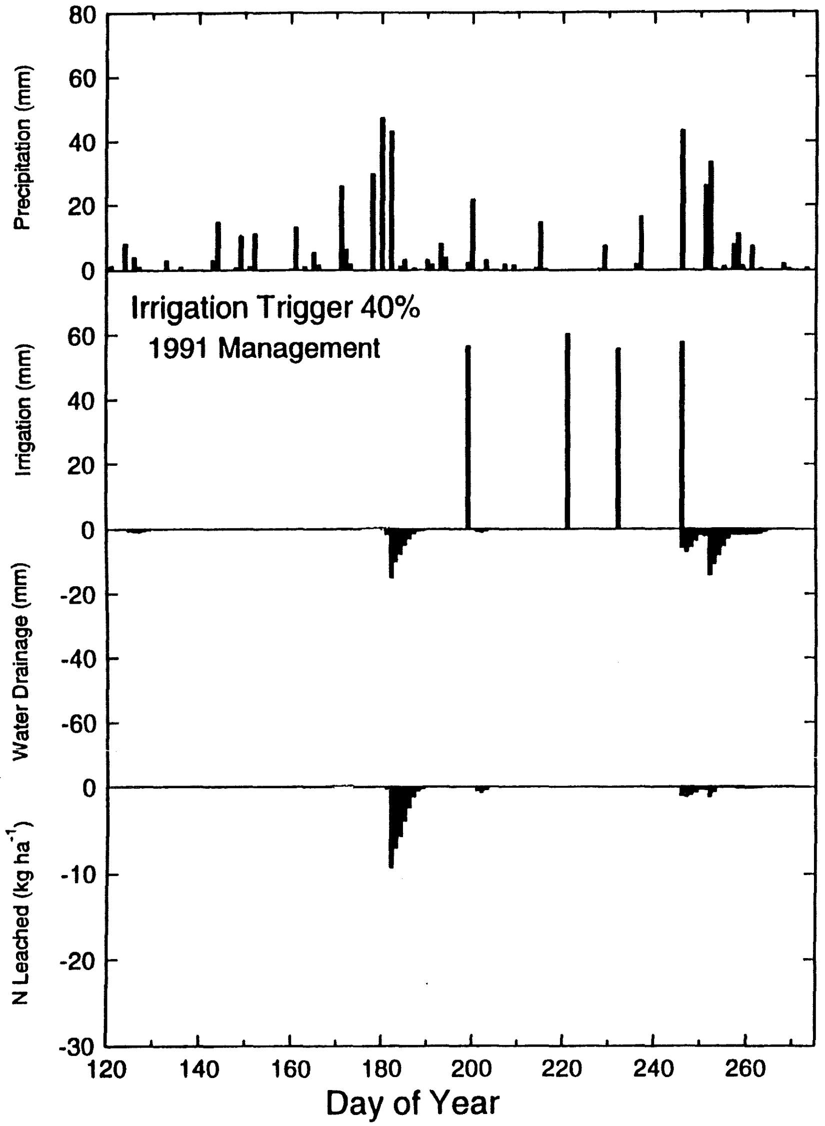


Fig. 1-7. Daily simulation of irrigation application, percolation, and nitrate-N leaching resulting from an irrigation trigger of 40% using 1991 weather and management with high N fertilizer rate (277 kg ha^{-1}) at Staples, MN.

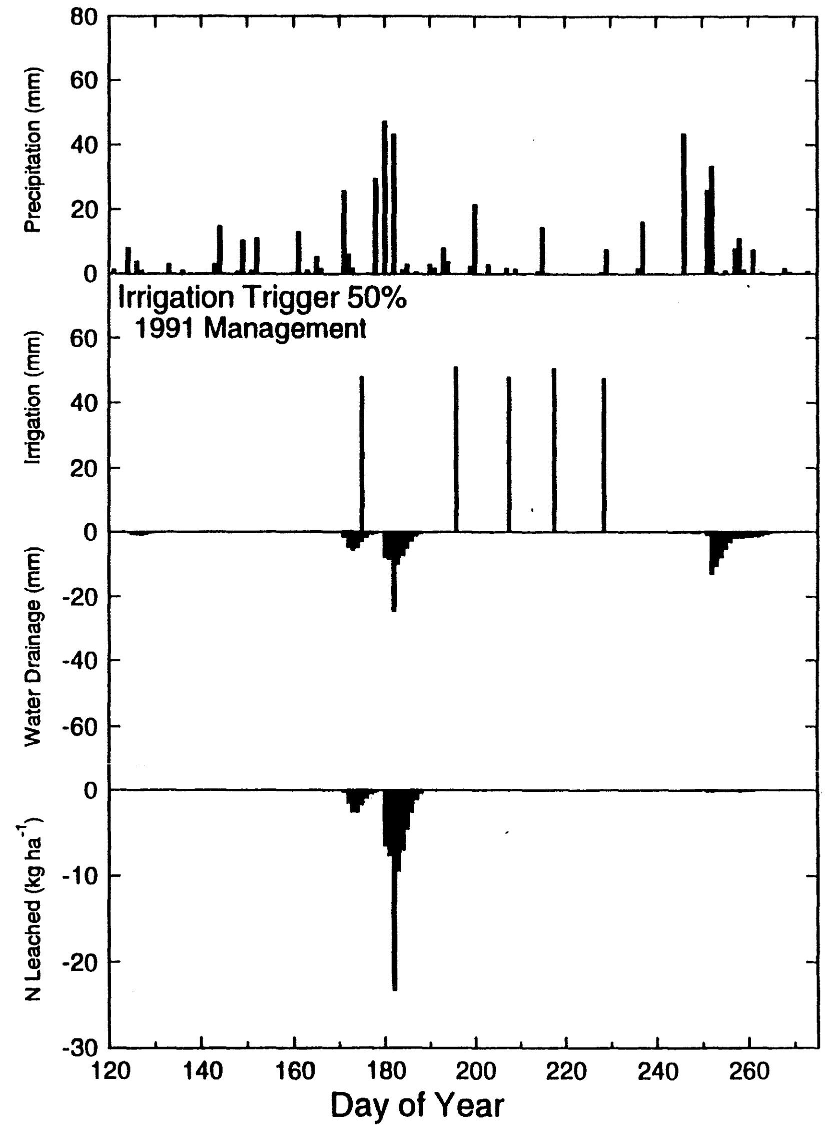


Fig. 1-8. Daily simulation of irrigation application, percolation, and nitrate-N leaching resulting from an irrigation trigger of 50% using 1991 weather and management with high N fertilizer rate (277 kg ha^{-1}) at Staples, MN.

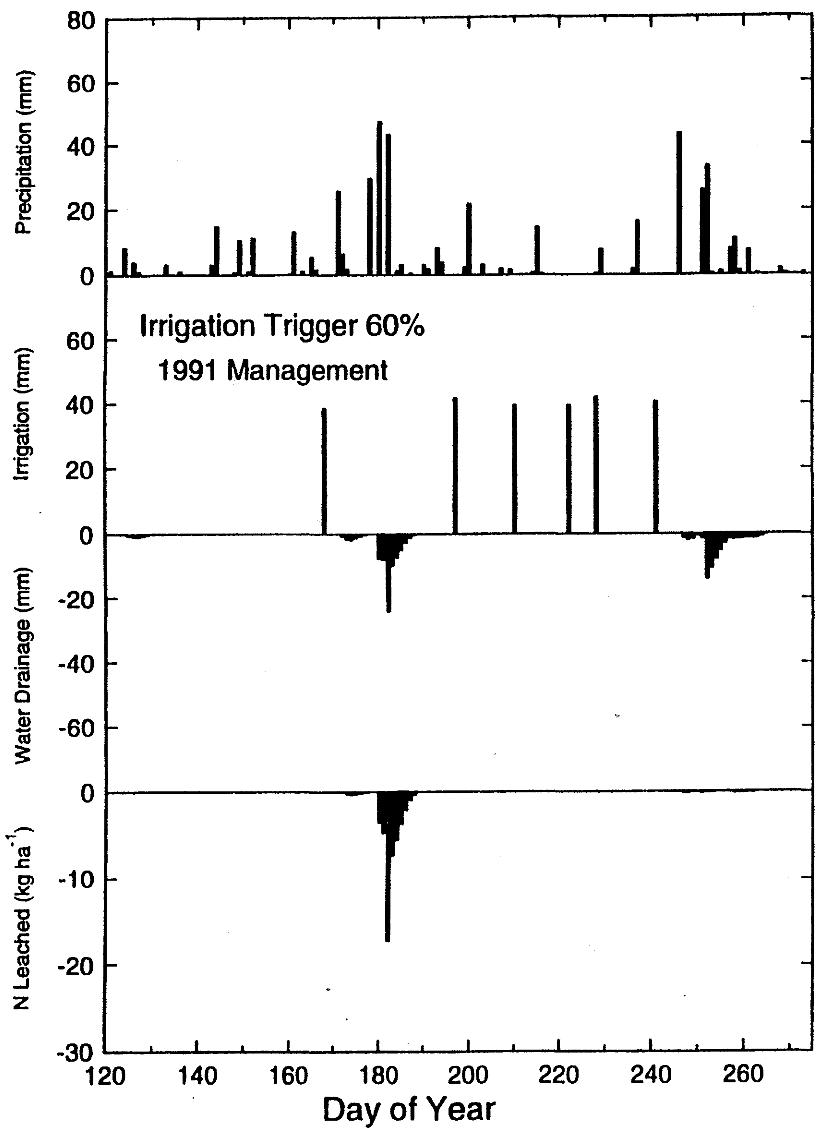


Fig. 1-9. Daily simulation of irrigation application, percolation, and nitrate-N leaching resulting from an irrigation trigger of 60% using 1991 weather and management with high N fertilizer rate (277 kg ha^{-1}) at Staples, MN.

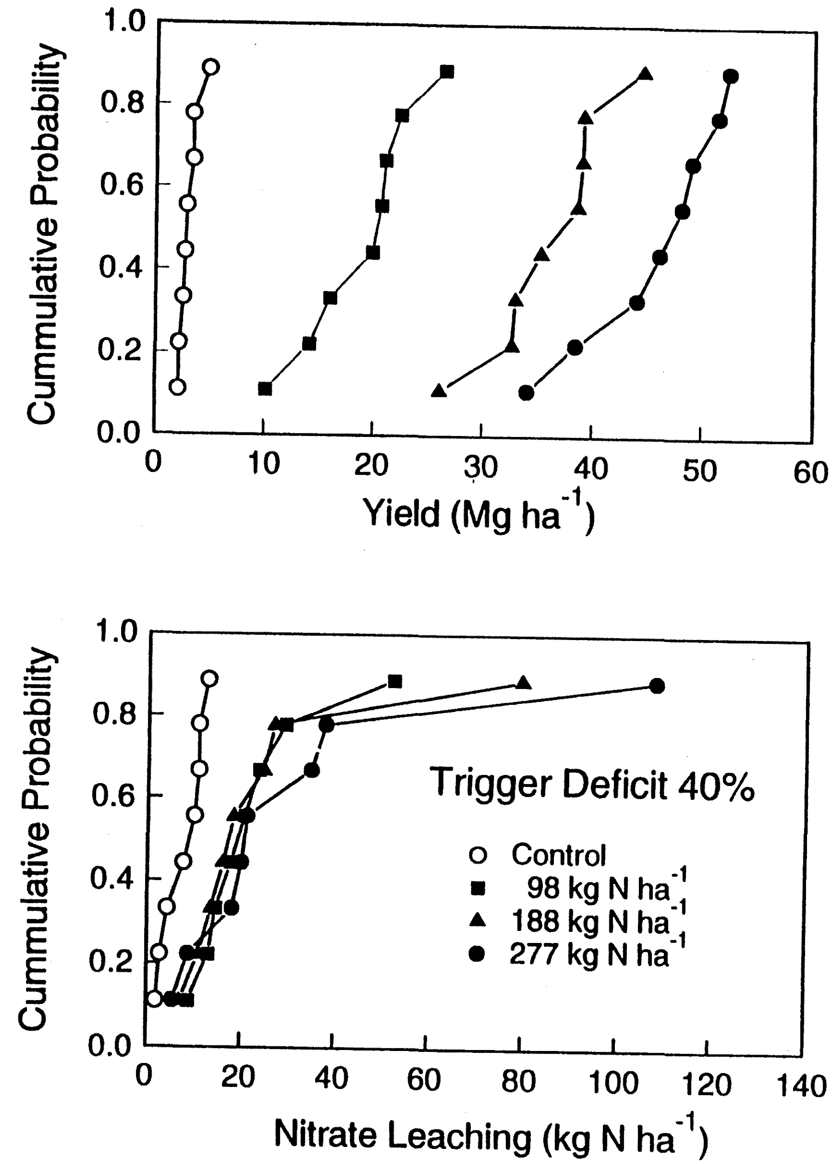


Fig. 1-10. Cumulative probabilities of potato yield and N leaching for four fertilizer treatments using irrigation trigger of 40% at Staples, MN. Cumulative probabilities are based on predictions from eight years of weather data.

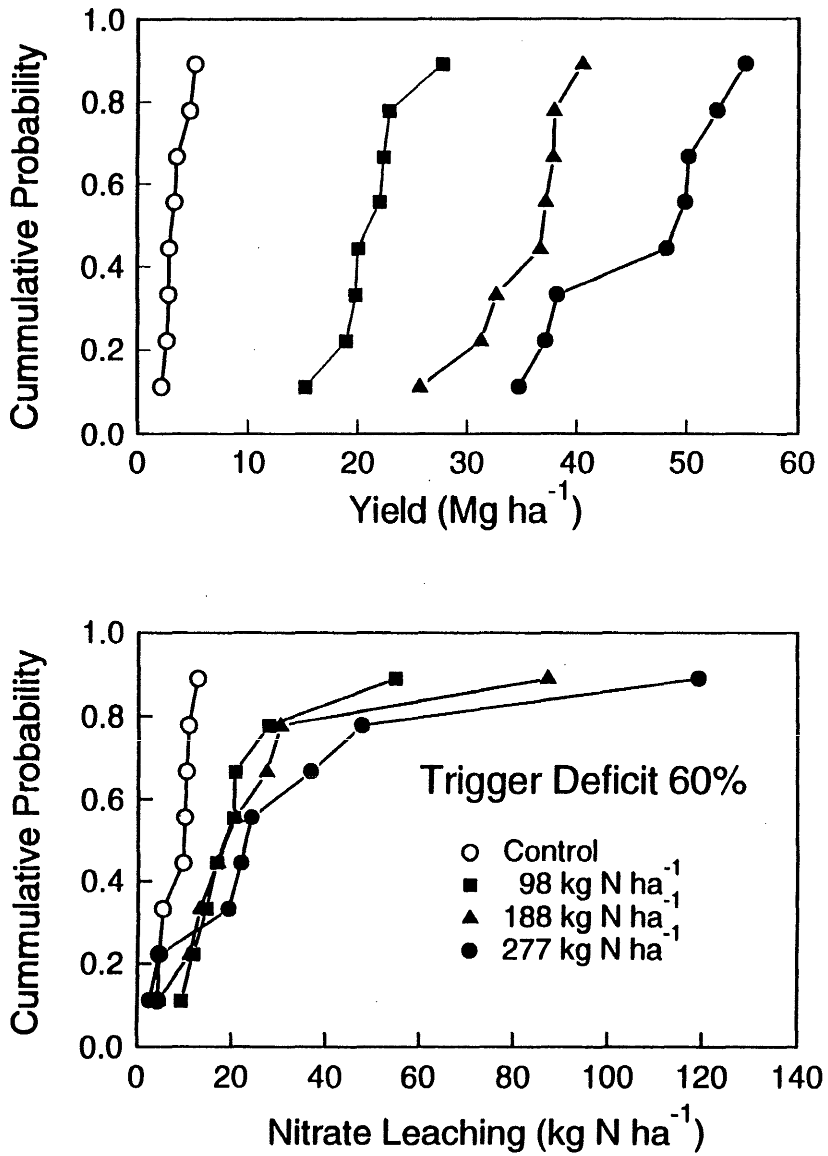


Fig. 1-11. Cumulative probabilities of potato yield and N leaching for four fertilizer treatments using irrigation trigger of 60% at Staples, MN. Cumulative probabilities are based on predictions from eight years of weather data.

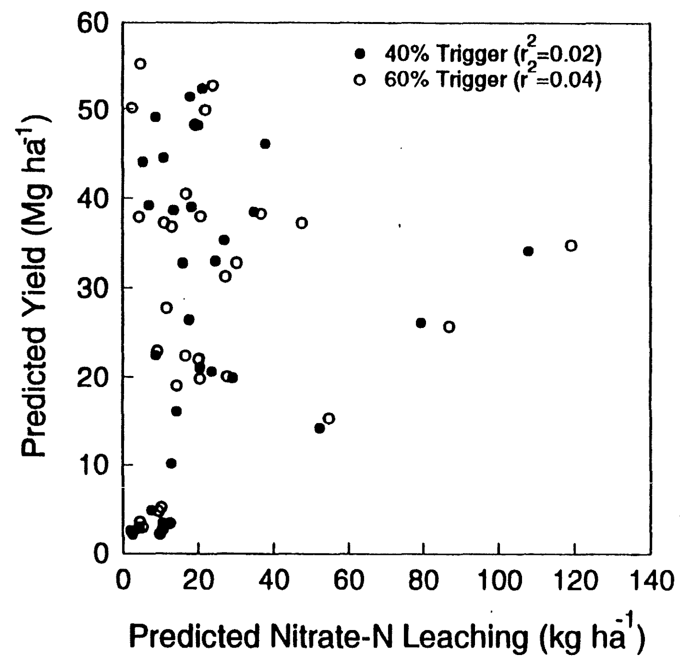


Fig. 1-12. Correlation between simulated yield and nitrate-N leaching for 40 and 60% trigger irrigation levels using eight years of weather data, with all other inputs set as for Staples 1991 simulations. All four N application rates (0, 98, 188, and 277 kg ha^{-1}) are included. Correlation coefficients (r^2) were computed across all N application rates for each trigger level.

Chapter 2. Characterization of the Prevalence and Initiation of Preferential Flow Paths in the Field

ABSTRACT

Use of most mechanistic modeling approaches for solute transport is mad more complex when preferential transport occurs. In order to evaluate the prevalence of preferential flow and determine the factors that tend to initiate its occurrence, a dye-tracing experiment using FD&C Blue #1 was conducted in the sandy Mollisol discussed in Chapter 1. Experimental treatments included a combination of three initial soil water contents (WET MEDIUM, and DRY) and three application rates (FLOOD, SPRINKLER-High, and SPRINKLER-Low) in an alfalfa field, plus two additional plots in an adjacent field with no history of alfalfa. We observed extensive preferential dye movement under FLOOD conditions, regardless of initial soil moisture or recent vegetation history. Preferential flow path lengths resulting from the two SPRINKLER rates were much shorter. Within-plot variability was very high. The major initiators of PFPs were decayed roots, followed by the abruptness and topography of the boundary between the Ap and Bt horizons. Characteristics of the horizon boundaries also a played a role in determining the pathways of dye movement. Open burrows were not common, though they did cause extensive preferential flow in the two non-alfalfa plots. While the shorter PFPs observed with the sprinkler rates suggest that preferential flow is not important under unsaturated conditions, we caution that interpretation of dye traces must take into account variable dye retardation (relative to the wetting front) under different application rates, and due to variability in the amount of adsorption between horizons. In this study, dye traces discerned pathways and relative extent of preferential transport of this moderately sorbed chemical under the imposed treatments, but these dye pathways may not reflect patterns in movement of water or other chemicals.

INTRODUCTION

High nitrate concentrations have been found in the groundwater of central Minnesota (Myette 1984). Preferential transport of water through soil leads to accelerated transport of chemicals to groundwater - that is, movement faster than predicted by most computer models. Faster-than-predicted chemical movement out of the root zone is undesirable from both ground water quality and agricultural production perspectives, since once a chemical moves below the root zone, it no longer accomplishes its intended purpose. Computer models are often used for evaluating various crop management systems (e.g., irrigation and fertilization strategies) for their ability to maintain satisfactory yields while minimizing or decreasing chemical movement below the rooting zone. However, current crop growth models generally use water and solute flow algorithms that do not account for preferential flow. In order to improve the predictions of models, it is desirable to evaluate the occurrence of preferential flow in the soil, and if it is significant, to modify the model to include preferential transport phenomena.

Numerous studies have reported the occurrence of preferential solute transport, giving evidence that preferential flow is widespread (Jury and Roth, 1990). Numerous theoretical and laboratory analyses have investigated different mechanisms for preferential flow including macropore flow (e.g., Munyankusi et al., 1993), unstable flow (e.g., Hill and Parlange, 1972; Raats, 1973; Philip, 1975; Hillel and Baker, 1988; Glass et al., 1989; Selker et al., 1992), and funnel flow (Kung, 1990b; Ju and Kung, 1993). Field studies have demonstrated the occurrence of preferential movement of water or solutes through macropores and cracks (e.g., Beven and Germann, 1982), as a result of soil layering characteristics (Kung, 1990a; van Weesenbeeck and Kachanoski, 1994), and as a result of hydrophobicity (Ritsema et al., 1993). Other field studies documented the occurrence of preferential transport, without attempting to discern the responsible mechanism(s) (e.g., Flury et al., 1994), or have set out to observe the occurrence of a specific mechanism (e.g., Glass et al., 1988; Starr et al., 1978, 1986). Few studies, however, have been designed to evaluate the relative importance these different mechanisms played in a given field situation.

Observations of soil morphologic features at our field site suggest that one or more of these mechanisms could be occurring. The contrast in hydraulic properties between Ap and Bt horizons allows for the possibility of water buildup above the Bt such that lateral flow is obtained which could 'funnel' water into individual vertical channels of preferential transport. Distinct depositional beds with alternating coarse and fine layers were observed in preliminary site investigations could act similarly. The contrast between the hydraulic conductivity of the Bt and the underlying 2BC horizon (higher hydraulic conductivity) is a situation that could be conducive to the development of fingering. Interpedal cracks and earthworm burrow-induced macroporous flow is unlikely since there is only weak structure and the abrasiveness of sand is not conducive to the presence of earthworms. Potentially more important macropores may result from root channels, especially plants with tap roots (Zins et al., 1991), and faunal burrows formed by insects such as ants (Wang et al., 1991).

Observations of the soil characteristics at several locations at our field site also found deep, iron-stained non-calcareous vertical features 10 to 20 cm in diameter penetrating into the calcareous parent material (glacial outwash) for one or more meters, that we suggest are historic PFPs. We speculate that the carbonates have been leached out of these features by preferential diversion of water into these areas, bypassing the adjacent areas that have consequently retained their calcareous nature. These features may be relict features formed before the advent of agriculture in the area.

The objective of our study was to evaluate the extent of preferential transport (if any) of a moderately sorbing solute and to evaluate which of the soil features described above (if any) play a role in initiating preferential flow paths. Furthermore, different mechanisms may be important under different soil wetness conditions so we conducted the study at several combinations of initial soil moisture and application rates. Lastly, we wanted to evaluate whether observed PFPs would correspond to the historic PFPs (the deep, iron-oxide stained, non-calcareous zones).

METHODS AND MATERIALS

Experimental Site

To achieve the above objectives, we set up a field experiment using a dye tracer with replicated 1m by 1m plots. We considered replication important to see if the patterns observed with respect to imposed treatments were consistent, or if soil heterogeneity outweighed observed patterns. This experiment was conducted at the Central Minnesota Economic Development Research and Education Center (formerly the Staples Irrigation Center) in central Minnesota near the town of Staples, in Autumn 1993. The field chosen for the experiment was in the Conservation Reserve Program (CRP) and had been planted to alfalfa five years previously. Two additional plots were studied in 1994 about 100 m away in an uncropped alley way whose adjacent fields had no history of alfalfa. The soil is a Udic Argiboroll (Verndale sandy loam), formed in sandy glacial outwash. It consists of an 18-25 cm thick Ap horizon underlain by a sandy loam argillic horizon that is about 14 cm thick. Below this are sandier 2BC and 2C horizons. Typically this soil is used for irrigated potato, corn, and/or kidney bean production. Slopes are minimal (0-2 %).

Dye Characteristics

The dye we used was FD&C Blue #1, also known as C.I. Food Blue 2, and as Brilliant Blue FCF (Disodium salt of ethyl [4-[*p*[ethyl (*m*-sulfobenzyl)amino]-*a*-(*o*-sulfophenyl)benzylidene]-2, 5-cyclohexadien-1-ylidene] (*m*-sulfobenzyl) ammonium hydroxide inner salt). This anionic (or neutral, depending on pH), non-fluorescent dye was chosen for the good contrast between its bright blue color and our soil, its low toxicity (recently reviewed by Flury and Flühler, 1994), and for its relatively low retardation (recently evaluated also by Flury and Flühler, 1995). More information on the characteristics of the dye are given in Chapter 3, as well as in Flury and Flühler (1995). Preliminary laboratory work with saturated columns showed that it moved through the Ap horizon of our soil more quickly than Rhodamine WT.

Plot Setup

Three replicates of each treatment were installed in three blocks as shown in Fig. 2-1. (In the end, third replicate was never excavated, and is therefore not discussed further.) The treatments were three initial moisture conditions (WET (W), MEDIUM (M), and DRY (D)), and three application rates ('FLOOD' (F), 'SPRINKLER-High' (Sh), and 'SPRINKLER-Low' (Sl). The specifics on these treatments are given below. Within each replication, plots with the same initial moisture conditions were laid next to each other. Application rate was randomized within the moisture content groupings.

Prior to plot installation, each of the plot areas were rototilled to 8 cm in order to disrupt macropore continuity with the surface. Plastic lawn-edging was used for plot borders, and was installed several centimeters into the soil. Soil was banked against the outside of the borders to provide additional stability.

Following border installation, pre-irrigation (using sprinklers) was applied to establish the different initial moisture conditions. Only treatments designated WET and MEDIUM received pre-irrigation. DRY treatments received no pre-irrigation, and were covered during the pre-irrigation to avoid potential drift from adjacent WET and MEDIUM plot areas. The use of rain gages throughout the plot areas showed that there was some non-uniformity in the amount of water applied to the different plot areas due to windy conditions. Irrigation to all WET and

MEDIUM plots was continued until at least 130 mm water had been reached at each point. 130 mm water would penetrate to about 55 cm under conditions of uniform, piston-like flow (no dispersion), with all depths above this 'field capacity'.

Dye Application

WET plots had dye applied immediately after stopping pre-irrigation, while MEDIUM plots were covered after irrigation and dye was not applied until two days later. Therefore the MEDIUM plots had two days drainage before dye application. DRY plots received dye application at the same time as the WET plots. Gravimetric moisture samples were taken between plots at the start of dye application in each soil wetness grouping.

All plots received the same amount of dye (200 g) dissolved in the same quantity of water (130 liters) - 130 mm solution in all. The only difference in dye application was the time period over which dye was applied. FLOOD plots were instantaneously ponded with a head of about 4 cm until all dye solution was added. It took less than one hour for all of the dye solution to infiltrate into these plots A folded burlap sack was placed on the soil surface to minimize surface disturbance during dye additions. The SPRINKLER-High and SPRINKLER-Low treatments were designed to simulated unsaturated water flow conditions. Dye solution was applied using a hand-held spray wand connected to a constant pressure (60 psi) regulator on a field sprayer with large mixing tanks typically used for pesticide application (field spray booms were disconnected). SPRINKLER-High plots received four 14-sec applications each hour for two days, while SPRINKLER-Low plots received two 14-sec applications over four days. No applications were made at night due to difficulty in seeing the plots and spray wand. Nine applications were made each day. Evaluated on an hourly basis, the application rates were 3.8 mm h^{-1} for SPRINKLER-LOW, 7.6 mm h^{-1} for SPRINKLER-High, and about 130 mm h^{-1} for FLOOD plots. These application rates correspond to 28%, 55%, and 940% of the lowest saturated hydraulic conductivity in the soil profile (Bt horizon).

The application spray wand consisted of two nozzles 19 cm set up to allow even distribution over the 1 m width of the plot. The spray wand was kept level and at a constant height above the surface (50 cm) using weighted strings on each end. For all SPRINKLER plots, application intervals were measured with an audible stopwatch and individual application passes alternated direction with each application - i.e., first north-to-south, then east-to-west, then south-to-north, etc. Between applications, each plot was covered with clear plastic to minimize evaporation. At the end of dye application, large plastic tarps were laid over the plot areas (in addition to the small plastic covers over individual plots) until they could be excavated.

Due to logistics (including lack of time before soil freezing, and cave-in of one plot) only one complete and one partial replication could be examined. Therefore this paper reports results of two replicates each of WF, MF, DF, WSh, and DSh, and one replicate each of WSl and DSl - 12 plots in all. The following summer, two additional plots with no history of alfalfa were also examined (described below).

Summer 1994 (no alfalfa) Plots

The procedure described above was repeated at two additional plots in late summer 1994 at an adjacent uncropped location of the same soil type that had no history of alfalfa within at least ten years. These plots allowed comparison with dye patterns in the same soil that had a different rooting history. Since the majority of the deep preferential flow paths occurred in the F treatments, only F treatments were imposed at this site. All experimental procedures were the same as described above for the Fall 1993 plots, except that there was no pre-irrigation. In addition, this time bromide ion (as KBr) was added to the dye solution at a rate of 120 kg Br^{-1} ha^{-1} to evaluate differences in flow paths of adsorbed and nonadsorped tracers.

Excavation of Plots

Plots were excavated sequentially from the southeast (Rep 1) and the southwest (Rep 2) depending on the time of day (Fig. 2-1). Orientation of the plots was designed to optimize light conditions on excavated profile faces in morning (southeast exposure) and in the afternoon (southwest exposure) - maximizing the number of profiles that could be examined in a day. As well, the linear nature of the layout minimized the amount of excavation needed to maintain a camera distance of at least 3.5 m from the profile face. A large distance was desirable to minimize photographic differences as subsequent faces were exposed, each further away from the stationary camera.

Eleven successive vertical profile faces at 10-cm intervals were examined in each plot, beginning with the edge of the plot which was designated the "0 profile". Examination consisted of digging back to the given increment and preparing a smooth, clean face using brick-layer trowels, which was then photographed. Notes were made in the field of the depth to horizon boundaries, characteristics of the horizon boundaries, maximum depth of the most significant (deepest) dyed zones, and morphologic features that appeared to be related to the development of preferential dye paths.

For each profile face examined, we used the following procedures to establish true vertical conditions and maintain a consistent coordinate system. Prior to plot excavation, construction-grade wooden boards (2 cm by 15 cm, i.e., standard "1 by 6" boards) were installed in the soil outside of the plots parallel to the left and right sides as seen when examining a profile face. The top edge of each board extended about 2.5 cm above the soil surface (see Fig. 2-2), and was leveled with the board on the other side of the plot. This arrangement allowed a third board to be laid across these, parallel to both the plot surface and plot face, which served to maintain an accurate vertical and horizontal coordinate system across the entire plot. The top of the horizontal board was designated coordinate y = 0 (vertical direction), while the left edge of the plot was designated x = 0 (left-to-right direction). The two embedded parallel boards were marked in 10 cm increments beginning with "0" at the front edge of the plot (first profile excavated) which was considered the w direction. In order to record coordinates on the photographs and to facilitate excavating into the plot to exactly the w coordinate desired, six 2-cm diameter metal washers (with orange centers) were hung from the top of the board using nylon line. They extended 50 and 100 cm below the top of the board at x = 0, 50, and 100 cm across the face. When the washers just barely hung freely we knew that the face was truly vertical. In this way, after correction for the height of the y=0 coordinate above the soil surface, accurate x, y, and w coordinates were established and could be recorded on the photographs. The washers served as "tie points' for determining location coordinates later in the analysis stage.

Color slide photographs (Ektachrome daylight) were taken with a tripod-mounted 35 mm camera (manual adjustment of speed and f-stop settings) placed at least 3.5 m from the first profile face ("0" profile). The same camera position was maintained for all profiles within a given plot in order to minimize distortion differences between profiles. Photographs were taken both in a naturally dry state as well as after misting with water using a plant mister. Photos taken in the dry state gave a good record of soil horizonation, since the sandier horizons quickly dried and lightened in color. Misted photos allowed a better record of moist soil colors.

Dye Pattern Analysis

For each profile face, the photographic slide was projected on a wall, and edges of the dyed area were traced on 3 mil mylar resulting in traces about 20 cm by 20 cm. Individual dye "polygons" were assigned unique codes for identification purposes. During the tracing procedure distinctions were made between regular dyed zones and those in which the dye was very pale. This distinction was made to allow flexibility in analysis of dye coverage. In this manuscript, however, all of the analyses presented have combined the regular and "pale" dyed areas.

The pencil traces were then hand-digitized and analyzed using ARCINFO ver. 6.1. Washer centers as well as the intersections of fishing line with the top of the horizontal board were used as tie points to register each trace to the same coordinate system, and to correct for slight photographic distortions. A minimum of six tie points were used for each trace. Transformation errors were generally less than 7 mm (field coordinate system). Calculations were then made of the total area of each dye polygon. Dye distribution with depth was calculated by converting the ARCINFO vector images into raster files with a one-half by one-half centimeter grid (200 cells = one meter). The resulting "x,y, dye-code" data file was used to determine the number of dyed cells in each depth (going through the public domain GIS program KHOROS and a simple program written in SAS).

Dye pattern quantification was conducted on 9 profile faces in each plot (10,.20,....90 cm into each plot). While they were photographed, the dye patterns for the profiles at the edges of the plot (i.e., the "0" and "100" cm profiles) were not quantified. Dye quantification was conducted on the part of the profile 25 cm below the soil surface and deeper due to difficulties in consistently separating the blue color from the dark A horizon. While the depth to the bottom of the Ap horizon varied from 20 cm to slightly over 25 cm, the 25 cm depth was used for all profiles to be consistent.

Supporting Measurements

During the examination of several profile faces, paired dye and no-dye intact soil cores (4.95 dia by 5.1 long) were sampled horizontally using a hand-held corer from the exposed profile face for measurement of bulk density and field moisture content. These cores were sealed into zipper-locking freezer bags until they could be weighed later the same day.

Infiltration measurements were made at both the alfalfa and no-alfalfa sites using double ring (positive head) and tension infiltrometers (negative head). Each method was replicated three times at each location - a total of 12 of measurements. Prior to infiltration measurement the areas were rototilled to a depth of approximately 8 cm to obtain surface conditions similar to those used in the dye experiments. Inner and outer rings were pushed several centimeters into the soil. The diameter of the inner ring was 300 mm. The soil surface within the inner ring was covered with about 5 mm of medium sand followed by a plastic kitchen cleaning pad to minimize surface disturbance. During ponded infiltration water was added to both inner and out rings. After setting the initial head of 45 mm, the amount of time required for each subsequent one liter to infiltrate was recorded. Constant head (45 mm) was maintained by slowly adding water to the inner ring so that the tip of a small wire remained just below the water surface. Measurements were made for at least 30 minutes, even though steady state conditions were established almost immediately.

Tension infiltration rates were measured immediately following double ring measurements in the same locations. Tension of -35 mm was applied using a mariotte system - which excludes water from entering soil pores larger than 0.4 mm. A 37 μm pre-wetted nylon mesh was used at the base of the infiltrometer. Tension infiltration rates were measured by reading the height of water in the reservoir at one-minute intervals for 30 minutes after starting each measurement.

Samples for analysis of bromide ion in the profile were collected from one profile face in each of the no-alfalfa plots using 4.95 cm dia. by 5.1 cm long soil cores. In addition to bromide analysis, these cores were used to determine bulk density, field water content. Samples were several depths at 10 cm intervals across each profile (that is at 10, 20,...90 cm across). Bromide was extracted from soil using 0.005*M* $NaNO_3$ in a 1:1 soil:solution ratio, centrifuged for 11 min at 4000 rpm to remove colloids, and analyzed using an ion-specific electrode. Electrode readings were recorded after 90 sec immersion, standards were rerun about every ten samples, and the electrode membrane was polished every thirty samples. Three sets of soil that did not receive bromide application were collected from each horizon near the site and used for determining bromide detection limit (mean plus three times the standard deviation of the blanks). Dye concentration was also determined from the same extracts using UV/Vis spectrophotometer at 629 nm to allow comparison of dye and bromide contents for each location.

RESULTS AND DISCUSSION

Soil Characteristics

General soil characteristics of Verndale sandy loam are given in Table 2-1. Most of these measurements were made about 200 m from the study site by Sexton (1992) or Pang (1995). Soil pH was measured using soil from the study site and a combination pH electrode in the lab. Infiltration rates shown were measured as described earlier. No soil structure was observable while in place, however upon removal from the profile, the Ap horizon (below the rototilled zone) had a weak granular structure, and the Bt horizon had fine, moderate subangular blocky structure.

As expected, infiltration rates at both sites were significantly greater under saturated conditions compared to unsaturated conditions at -35 mm pressure ($p < 0.01$). At the alfalfa site, tension infiltration rates were only 38% of the saturated rates, while at the no-alfalfa site, the tension infiltration rate was 68% that of saturated. This indicates that at both sites, a large amount of water flow under saturated conditions occurs through large pores. Infiltration rates were also higher in alfalfa plots compared to no-alfalfa plots, suggesting that alfalfa roots have some influence on water movement.

Initial water contents for the different treatment are given in Table 2-2. The MEDIUM and DRY initial water contents were not significantly different. The lack of difference may be due to large scatter in the measured values (Table A2-1), such that more samples would have been required to elucidate the difference. It may instead mean that there truly was no difference, which indicates that most drainage occurs within two days after large moisture additions at the surface. Throughout this manuscript I have kept the labels for plot identification purposes.

Descriptions of Preferential Flow Paths

The most dramatic PFPs developed under FLOOD conditions.An example of the general shapes of dye paths observed, and the variability between nine profile faces separated by 10 cm is shown in Fig. 2-3. The PFPs were long, generally column-shaped features with slight rounding at the bottom. Shorter PFPs also occurred, but most of them remained in the Bt or 2BC. Both SPRINKLER application rates resulted in relatively more uniform dye fronts, and only short PFPs, generally only a few centimeters long, developed below this front. An example of the patterns and variability among the nine profiles from one SPRINKLER plot is shown in Figure 2-4. At all application rates the color boundary between dyed and non-dyed zones was usually very sharp, suggesting little lateral diffusive movement. Shorter PFPs (those that remained within the Bt or upper part of the 2BC) were less cylindrical in shape and often had more lateral components. There was no statistical difference field moisture content or bulk density between dyed and no-dye regions in a given horizon.

In several plots, especially under drier conditions, there were extremely intricate patterns of dye/no-dye with abrupt color boundaries between (Fig 2-5). This pattern was observed particularly in the 'no-alfalfa' plots, perhaps due to their relatively drier initial water content (lower than about 0.100 cm^3 cm^{-3} throughout the whole profile) and consequently lower hydraulic conductivity which limited lateral diffusive flow. There were no easily observable soil morphologic features that could be clearly related to these intricate patterns, therefore the mechanism(s) creating these patterns were not discerned. It is possible the fine patterns may have resulted from small features that were not easily observable - i.e., weak soil structure or fine root channels (< 0.5 mm).

Patterns in PFPs Among Treatments

Patterns in the fractional area of the profile that was dyed at each depth are shown in Fig. 2-6. Values shown are the means for each depth of the nine profile faces for a given plot. At each depth there was extensive variation in dye coverage among the nine profiles, as shown by the coefficient of variation (CV) (Fig. 2-7), as well as in plots for individual profile faces given in the Appendix. At depths of about 50 cm, CV approaches about 1.0 (100%) for most treatments, and approaches 3.0 (300%) near the bottom of the dyed zone of all treatments. This demonstrates a large variability in dye coverage between the nine profiles within each 1 m^2 plot.

The most extensive dye coverage occurred under FLOOD application, followed by both SPRINKLER treatments (Fig. 2-8). The differences in dye coverage between sprinkler treatments were relatively small. Also, the initial soil wetness does not appear to influence total dye coverage.

The patterns in maximum depth of dye penetration (Fig. 2-9) are similar to the dye coverage data in that FLOOD plots show deeper movement than either SPRINKLER treatment, and there is also little difference in the depth of dye penetration between the two sprinkler treatments. Within the alfalfa plots, deeper dye penetration is associated with initially WET soils in both replicates. However, there were some profiles in the no-alfalfa plots that had deep penetration similar to the WET plots, in spite of much drier initial water content. It is possible that this anomaly can be explained by differences in PFP initiation (next section). Our dye penetration data is similar to that of Flury et al. (1994) - that initially WET soils allowed deeper dye penetration in most cases.

Another index of the relative amounts of preferential flow is the number of PFPs as a function of depth (Fig. 2-10) for each treatment. PFPs that extended below 55 cm were considered 'deep PFPs' since 55 cm is the depth the dye front would have moved if it had moved uniformly with no dispersion and no chemical retardation by chemical interaction with the soil. We determined that this dye is retarded compared to the wetting front (Chapter 3), therefore, 'deep PFPs' were considered to be areas of significant preferential transport. The number of deep PFPs observed for each individual profile face are shown in Fig. 2-11.

In the FLOOD plots there are more PFPs near the surface under the driest initial wetness conditions (no-alfalfa plots), fewer under MEDIUM and DRY conditions, and fewest under initially WET conditions. When the number of PFPs at a depth are taken together, we can see that under drier conditions there are thinner and more distinct PFPs compared to wetter conditions (i.e., initial wetness influences the shape of dye patterns under the FLOOD conditions). This agrees with observations of Glass et al. (1988), though our PFP-initiating mechanisms may be different (discussed below). These observations suggest that model approaches may want to include these differences in shapes of PFPs with moisture condition. Under SPRINKLER conditions, there is no distinct pattern in the number of PFPs with respect to initial soil water content.

PFP Initiators

Field notes were made during excavation to record the features or mechanisms that appeared to have initiated the PFPs in each profile. Once the dye solution entered the Bt horizon (regardless of mechanisms), it continued to move vertically down with little or no lateral deviation, regardless of the material it passed through. For example, at least six cases occurred in which dye movement occurred along a root or decayed root through the Bt horizon, and continued to flow vertically even it the root bent lateral (e.g., along the bottom of the Bt horizon). Hence, we began to think of the soil features as preferential flow *initiators*, since flow established by one of these features continued to move vertically (i.e., by gravity) without regard to other morphologic features. Several different types of PFP initiators were discerned (Table 2-3). Roots and decayed roots, and Ap-Bt horizon boundary characteristics had the largest role controlling where PFPs were initiated. Krotovinas (filled burrows, originally excavated by ants and rodents) of one to eight centimeters diameter were very common, but generally PFPs were not affected by their presence. Open burrows were not common. As excavation progressed through the numerous profiles, our observations (and notes) became better due to evolution of apparent patterns. As a result, the summary of such features given the Table 2-3 must be evaluated qualitatively rather than quantitatively. However, in spite of these limitations, it does show the overall pattern in prevalence and importance of the various PFP initiators present.

Roots

Roots/decayed roots provided the most important PFP-initiating mechanism for the very deep PFPs in the alfalfa flood plots. An example of the relationship between a decayed root and a PFP is shown in Fig. 2-12. The importance of roots as PFP initiators became increasingly apparent over the course of excavating the numerous profiles. The category of 'undifferentiated' roots includes both decayed and live roots. With hindsight, decayed roots were the most important type but the relative percentage was not recorded for most plots. It was not necessarily all roots (decayed or live) that were important, as there were often roots that were unstained and not associated with PFPs. The pattern we observed was that deep PFPs were associated with decayed roots that crossed the Ap-Bt horizon. The decayed vascular tissue tended to keep a partially open channel (loose sand could not fill it up), and thus provided an inlet for dye solution to enter the lower-permeability Bt horizon.

Roots and decayed roots were not important for conducting dye in the 'no-alfalfa' plots. However, the differences in the role of roots between the alfalfa and no-alfalfa plots is not due to a lack of deep taproots in the 'no-alfalfa' plots. Numerous other decayed taproots were observed, apparently from weeds. It seems likely that the channels maintained by the decayed vascular tissue in these roots should be equally conducive to initiating PFPs as decayed alfalfa roots. It is possible that the difference in dye conduction is due to differences in the types of roots, however it seems more likely that it is due to the diversion of the dye solution into open burrows described below.

Open Burrows

Open burrows were not common and did not play any role in most plots. Only one open burrow in each of the no-alfalfa plots was observed. However each of these burrows (about 2 mm diameter, likely made by ants) was responsible for all but one of the deep PFPs observed in these plots (Fig. 2-11). We suspect that these pathways diverted most of the applied dye solution into themselves due to rapid movement, such that little water was available for deep movement in other parts of the plots.

In both plots, the open burrows curved laterally and opened into larger 'chambers' within the Bt horizon. The PFPs continued vertically below the bottom of these chambers. Directly below the chamber of the first no-alfalfa plot (F1), in the center of the PFP was a vertical line of unstained sand (about 5 mm diameter) and organic material which appeared to be highly-decayed root material. The sand did not appear to be connected to the chamber. This sand was loose and likely had greater porosity and larger pores than adjacent dyed areas. It seems likely that dye solution in the surrounding dyed areas never had great enough hydraulic head to overcome the water entry pressure of this undyed zone.

Interestingly, the darker organic matter-rich soil within the burrow and chamber showed no blue color either. This suggests that the dye solution moved along the outside of the burrow but did not enter the burrow, perhaps again due to water entry pressure barrier. We can not discard the possibility that dye indeed had entered the burrow and chamber, and was no longer visible either due to degradation or adsorption such that blue color was lost. However only four days had passed since dye application to this plot, and blue color was visible in other Ap soil for at least seven weeks in other areas. Dye was still clearly visible in the Bt horizon 20 months after application , though not in the Ap. Some of the other plots showed a similar pattern of no blue color in the Ap below the rototilled zone (e.g., DF - rep 1). In these cases we could not tell if this was due to complete bypass of the Ap in these profiles, due to dye degradation or due to loss of blue color due to adsorption. This uncertainty was another reason for not quantifying dye above 0.25 m.

Horizon Boundary Characteristics

Two types of horizon boundary characteristics played a role - distinctness and shape. Both abrupt and gradual boundaries were observed in all plots. The abrupt boundaries were created by plowing. The gradual boundaries could be described as 'mixed' Ap and Bt material. The term 'mixed' includes two different cases. The first is where A horizon inclusions occur in the upper Bt horizon (perhaps due to insect or root activity), and would be described as A/Bt if it had a larger lateral extent. The second case is where the A horizon extends more deeply than the plow zone, which would be described as a transition ABt or as A2. Practically speaking, these cases are two ends of a spectrum, and in the field they were not always distinguishable (hence grouped together). In general, the lateral extent of mixed boundary zones was 4 to 30 cm.

'Mixed' Ap-Bt boundaries were prevalent PFP initiators (Table 2-3). A frequently observed pattern was that there would be an accumulation of dye at abrupt boundaries and deeper movement of dye in the areas where the boundary was mixed. This might be due movement of more dye and water into the mixed zones which appeared to have greater permeability (not measured) than the unmixed Bt horizon - i.e., deeper dye movement due to greater ease of water penetration in the mixed zones. An alternative explanation of the pattern is greater adsorption in the Bt horizon compared to the Ap (about an order of magnitude - see Chapter 3). It is possible that dye in the infiltrating solution was nearly instantly adsorbed where the boundary was abrupt and only Bt material was present, while it was more slowly adsorbed in the zones that had mixed A and Bt material. The resulting pattern for both the physical and chemical scenarios discussed would be shallow dye penetration at abrupt boundaries and deeper dye movement in the mixed zone. In other words, it is possible that the patterns observed are due to either or both of these causes, though the relative importance can not be determined from our observations.

Sloping Ap-Bt was not common (since plowed to a uniform depth). However, in some cases small 'hills' a few centimeters tall and wide did occur (Fig. 2-13). In these cases the dye tended to run along the two 'sides' of a hill (when looked at in a two-dimensional profile) and infiltrate the Bt at the 'toeslope' of the hills. These patterns are similar, though smaller in scale, to the deeper movement of solutes in the tongue portions of an irregular B-C horizon boundary observed in a sandy soil by van Weesenbeeck and Kachanoski (1994).

Generally PFP penetration due to horizon boundary characteristics was not as deep as seen for root-initiated PFPs, but the boundary characteristics were still important in that dye moved into only one or two selected parts of the profile face, bypassing the rest. The deeper dye penetration resulting from root initiation might have been due to rapid diversion of a large proportion of incoming volume into the root PFPs, leaving little solution remaining for slower downward movement within the soil matrix. An additional reason why dye moved more deeply in root-initiated PFPs is that there was little time for adsorption of the dye onto the soil due to rapid flow conditions in these paths, while in the mixed boundary areas there was more time for dye adsorption due to slower water movement (lower conductivity)

Effect of Variable Dye Retardation on Interpretation of Results

There are two types of variability in dye retardation that can be important when interpreting patterns of dye movement in a soil. The first is variation in retardation due to differences in application rate. The second is variation in the amount of retardation in space, which includes both within-horizon variability and variability between horizons. Related laboratory work (Chapter 3) indicates that decreasing application rate from FLOOD to our SPRINKLER-High rate increased the amount of dye retardation relative to the wetting front. In other words, the different application rates we used apparently caused differences in the amount of dye retardation between treatments. The occurrence of application rate-dependence in the amount of retardation has implication for interpretation of dye patterns. It means that although we can evaluate the effect of our different field treatments on movement of this dye, we cannot evaluate the extent of preferential water flow between the different treatments. In other words, even though our experiment demonstrates that the depth and prevalence of preferential dye flow paths is higher under FLOOD conditions compared to SPRINKLER, we can not extend this to say the patterns in movement of water (or other solutes) between treatments are different. Preferential water flow may be equally prevalent under both application schemes but undetected by our methodology.

The effects of variation in dye retardation with space is also important when interpreting our results. Laboratory work conducted after the field experiment (Chapter 3) found that the Bt horizon has almost an order of magnitude higher dye adsorption compared to the Ap and C horizons. Our initial idea was that variations in depth of dye movement would be due to physical factors - i.e., one of the PFP-initiating mechanisms discussed in this paper. However variations in chemical properties between Ap and Bt (and other horizons) are important too. For example, consider the case of a uniform wetting front in a soil that has two horizons with identical physical properties but the surface horizon has a lower adsorption capacity than the underlying horizon, and the horizon boundary is not perfectly uniform or horizontal. In this example, the dye could remain higher in the profile in locations where the underlying horizon (e.g., Bt) is closer to the soil surface, but move more deeply where the boundary is deeper in the profile solely due to chemical variations between the horizons and the characteristics of the boundary between. The resulting dye patterns might result in the incorrect interpretation that *water* moved preferentially in PFPs (which it had not), while actually only the *dye* moved preferentially. Similar phenomena could potentially occur within a horizon due to plant residues or similar variations in horizon composition.

In most soils, both chemical and physical characteristics generally vary between and within horizons, making the interpretation of dye patterns even more difficult. We can evaluate the extent to which the dye patterns diverge from the wetting front by comparing the distribution of dye (Fig 2-14) and bromide (Table 2-4) in the two no-alfalfa plots. Bromide moved much more deeply than the dye in these plots, which was expected since bromide was not expected to be adsorbed in the soil. The bromide distribution is also much more uniform than the dye - suggesting that the pathways followed by the two chemicals were different. The spatial resolution and techniques for collecting the two sets of chemical distribution are different, and the bromide concentrations in the extracts were near the limit of electrode detectability. Therefore, it would be beneficial to conduct additional research evaluating the apparent difference in distribution of the two tracers before making firm conclusions. However, since similar patterns were seen in the two separate plots, it seems plausible that there may indeed be a difference in movement.

Other Results and Comments

No 'funnel' flow along depositional beds was observed. One of our initial hypotheses was that depositional beds would be important to preferential flow at this site, since such depositional beds were observed in preliminary site investigations. However, these layers were rarely observed in our plots - likely due to mixing of the profile by several thousand years of burrowing animals. When such beds were present, they were deeper than the terminus of the PFPs or the PFPs were not present in the portion of the profiles containing depositional patterns. A few PFPs were observed that might be attributed to unstable flow. These occurred as short, finger-like protrusions at the Bt-2BC boundary, extending below the dye front under SPRINKLER conditions. Some of these protrusions could be attributed to roots or krotovinas, however for a few, no such initiating features were observed. Hydrophobicity may also have been a PFP initiator (since it is frequently observed in sandy soils), but we did not evaluate the hydrophobic characteristics of this soil. Hydrophobicity may also have been a PFP initiator (since it is frequently observed in sandy soils), but we did not evaluate the hydrophobic characteristics of this soil.

We observed fewer examples of the historic PFP features than we expected based their prevalence at the sites of our preliminary investigations. Where we did see them, there was not correlation with dye paths. Generally these features began more deeply in the profile than in preliminary sites, and often the PFPs present were initiated in other parts of the profile. The lack of relationship may reflect a change in PFP location since the development of the historic PFPs, perhaps due to the introduction of agricultural practices in the last 150 years which disrupted previously existing initiation locations near the soil surface.

The board-and-washer technique for maintaining our coordinate system worked well and is recommended for other researchers. Inevitably, true vertical conditions were usually much further into the plot than we would have thought if we had evaluated it by eye alone!

The dye pattern analysis procedure proved to be tedious. Initial attempts at dye quantification consisted of scanning color slides of the profile faces and then using KHOROS to make gray-scale images from the color scans, and then using binary segmentation to separate the dyed and undyed zones. This approach consisted of subtracting the blue band image (which had only soil-background gray tones) from the red band (which had both dye and background). Further image processing was used to get the binary image. However this approach was abandoned due to difficulties in developing binary conversions that had consistent separation of the dye from the background soil color in different slides. However, with hindsight, given the loss of resolution and precision (as well as tediousness) that occurs in the tracing-digitizing sequence, it may well have been worth it to have spent more time trying to develop the direct-scan analysis procedure.

CONCLUSIONS

We observed extensive preferential dye movement under FLOOD conditions, regardless of initial soil water content. Preferential flow paths resulting from either of the two SPRINKLER rates were much shorter. The effect of initial moisture was minimal. These observations are all similar to those of Flury et al. (1994) for multiple soils. In contrast to their multiple-soil study, we emphasized characterizing one soil type in detail, in order to evaluate the patterns in prevalence and initiating mechanisms of preferential flow paths. In our study we found that within-plot variability was very high. The most prevalent initiators of PFPs were decayed roots which served to maintain a somewhat open channel, followed by the abruptness and topography of the boundary between the Ap and Bt horizons. Open burrows were uncommon, but were the cause of substantial preferential flow under FLOOD conditions in the two no-alfalfa plots. In the decayed root channels we often found smaller live roots following these channels, likely due to the ease of penetration in these channels compared to the soil matrix itself. It seems probable that this pattern acts as a positive feed-back loop and that once this type of PFP-initiator is in place, it can continue to act as an initiator in the same location for many years.

This study has shown that patterns in PFP initiation can often be related to soil morphologic features which are readily available in soil surveys for many soils (e.g., roots, pores, horizon boundary characteristics). We suggest that this knowledge can be used to improve modeling approaches, and to speculate about likely mechanisms at other sandy soil sites, based on morphologic features.

While the shorter PFPs observed with the SPRINKLER rates suggest that preferential flow is not important under unsaturated conditions, we caution that interpretation of dye traces must take into account variable dye retardation. Dye traces show the pathways and relative extent of preferential transport of this moderately-sorbed chemical, but may not reflect patterns of water movement or movement of other chemicals. While the effect of variable dye retardation seems somewhat intuitive given knowledge of variability in soil chemical properties, we are surprised that this has not been considered in the numerous studies using dyes to evaluate preferential flow pathways.

REFERENCES

Flury, M. and H. Flühler. 1994. Brilliant Blue FCF as a dye tracer for solute transport studies - A toxicological overview. J. Environ. Qual. 23:1108-1112.

Flury, M., H. Flühler, W.A. Jury, and J. Leuenberger. 1994. Susceptibility of soils to preferential flow of water; A field study. Wat. Resou. Res. 30:1945-1954.

Flury, M, and H. Flühler. 1995. Tracer characteristics of Brilliant Blue FCF. Soil Sci. Soc. Am. J. 59:22-27.

Glass, R.J., T.S. Steenhuis, and J.-Y. Parlange. 1988. Wetting front instability as a rapid and far-reaching hydrologic process in the vadose zone. J. Contam. Hydrol. 3:207-226.

Glass, R.J., J.-Y. Parlange., and T.S. Steenhuis. 1989. Wetting front instability 1. Theoretical discussion and dimensional analysis. Wat.Resou. Res. 25:1187-1194.

Hill, D.E. and J.-Y. Parlange. 1972. Wetting front instability in layered soils. Soil Sci. Soc. Am. Proc. 36:697-702.

Hillel, D. and R.S. Baker. 1988. A descriptive theory of fingering during infiltration into layered soils. Soil Sci. 146:51-56.

Jury, W.A. and K. Roth. 1990. Evaluating the role of preferential flow on solute transport through unsaturated field soils. *In* Roth, K., H. Flühler, W.A. Jury, and J.C. Parker, eds. Field-scale water and solute flux in soils. pp. 23-28. Birkhauser Verlag, Boston.

Kung, K.-J.S.. 1990a. Preferential flow in a sandy vadose zone. 1. Field observation. Geoderma, 46:51-58.

Kung, K.-J.S.. 1990b. Preferential flow in a sandy vadose zone. 2. Mechanism and implications. Geoderma, 46:59-71.

Myette, C.F. 1984. Groundwater quality appraisal of sand-plain aquifer in Hubbard, Morrison, Otter Tail, and Wadena counties, Minnesota. U.S. Geological Survey. Water Resources Investigations Report. 84-4080.

Philip, J.R. 1975. Stability analysis of infiltration. Soil Sci. Soc. Am. Proc. 39:1042-1049.

Raats, P.A.C.. 1973. Unstable wetting fronts in uniform and nonuniform soils. Soil. Sci. Soc. Am. J.. 37:681-685.

Ritsema, C.J. and L.W. Dekker. 1994. How water moves in a water repellent sandy soil. 2. Dynamics of fingered flow. Wat. Resou. Res. 30:2519-2531.

Selker, J., P. LeClerq, J.-Y. Parlange, and T. Steenhuis. 1992. Fingered flow in two dimensions. 1. Measurement of matric potential. Was. Resou. Res. 28:2513-2521.

Sexton, B.T. 1992. Influence of nitrogen and irrigation management on corn and potato response and nitrate leaching. MS thesis. U. of Minnesota, St. Paul, MN.

Starr, J.L., H.C. DeRoo, C.R. Frink., and J.-Y. Parlange. 1978. Leaching characteristics of a layered field soil. Soil Sci. Soc. Am. J. 42:386-391.

Starr, J.L., J.-Y. Parlange, and C.R. Frink. 1986. Water and chloride movement through a layered field soil. Soil Sci. Soc. Am. J. 50:1384-1390.

van Wesenbeeck, I.J. and R.G. Kachanoski. 1994. Effect of variable horizon thickness on solute transport. Soil Sci. Sci. Soc. Am. J. 58:1307-1316.

Wang, D., K. McSweeney, J.M. Norman, and BAR . Lowery. 1991. Preferential flow in soils with ant burrows. *In* Gish, T.J. and A. Shirmohammadi (eds.), Preferential Flow, Proceedings of the National Symposium, American Society of Agricultural Engineers, Dec. 16-17, 1991, Chicago.

Zins, A.B., D.L. Wyse, and W.C. Koskinen. 1991. Effect of alfalfa (*Medicago sativa)* roots on movement of atrazine and alachlor through soil. Weed Sci. 39:262-269.

Table 2-1. Properties of the Verndale sandy loam. Infiltration rates were measured at our experimental site, and soil pH was measured using soil taken from our site. Unless otherwise noted, all other values were measured by Sexton (1992) in an area approximately 200 yards from our experimental site.

Horizon	Depth	Sand	Silt	Clay	Organic Carbon	Bulk Density	1:1 $CaCl_2$ pH	$\theta_{0.1MPa}$	$\theta_{1.5MPa}$	K_{sat}
	cm	------ g kg^{-1} ------			g kg^{-1}	Mg m^{-3}		--- cm^3 cm^{-3} ---		mm hr^{-1}
Ap	0 - 26	79	13	8	1.3	1.57	5.28	0.23	0.07	47.4
Bt	27 - 40	71	19	10	0.7	1.79	5.38	0.26	0.10	13.8
2BC	41 - 52	80	13	7	-	-	-	-	-	49.8
2C	53 - 100	92	5	3	-	-	5.74	0.13†	<0.04‡	120†

STEADY STATE INFILTRATION RATES

Pressure Head	Infiltration Rate: Alfalfa Plots	Infiltration Rate: No-Alfalfa Plots
mm	mm hr^{-1}	mm hr^{-1}
45	360	97.0
-35	139	65.3

† From X. Pang (1995)
‡ Water content measured at 1.2 MPa by X. Pang (1995) was 0.04 cm^3 cm^{-3}.

Table 2-2. Initial water contents prior to dye application. Each value is the mean of three measurements for 'Alfalfa' plots and 12 measurements for 'No-alfalfa' plots. Values are the standard deviations.

	Volumetric water content			
	Fall 1993 Plots (Alfalfa)			Fall 1994 Plots (No-alfalfa)
Depth	'Wet'	'Medium'	'Dry'	
cm	------------- cm^3 cm^{-3} ------------			cm^3 cm^{-3}
0 - 15	0.265 (0.038)	0.227 (0.027)	0.219 (0.008)	0.081 (0.003)
15 - 30	0.232 (0.012)	0.192 (0.009)	0.206 (0.012)	0.102 (0.007)
30 - 60	0.262 (0.026)	0.184 (0.015)	0.164 (0.014)	0.091 (0.006)
60 - 90	0.179 (0.022)	0.082 (0.008)	0.116 (0.022)	0.050 (0.006)
Total Water in 90 cm profile (cm)				
	20.7	14.3	14.8	7.0

Table 2-3. Tabulation of the prevalence of PFP initiators compiled from field notes. The number in a column indicates the number of profiles that had one or more PFPs which appeared to have been initiated by the corresponding type of feature. These results need to be interpreted in a qualitative (not quantitative) way, since over the course of excavation certain patterns became apparent, which made our later field records more complete than earlier records. Note that more than one type of initiator may be found in the same profile.

Profile	------ Roots ------				Open	Ap-Bt Boundary		Other	TOTAL
	UnD.	Dec.	Bent	Krot.	Burrow	mixed	slope		
WF-rep 1	7	1	1	2	1	5	0	1	18
WF-rep 2	3	0	0	0	0	5	0	0	8
MF-rep 1	7	0	0	1	0	2	0	2	12
MF-rep 2	5	1	1	1	0	2	0	0	10
DF-rep 1	5	5	4	0	0	1	0	0	15
DF-rep 2	3	8	0	0	0	0	0	0	11
WSh-rep 1	5	1	0	1	0	4	0	1	12
WSh-rep 2	6	5	0	2	0	0	0	0	13
DSh-rep 1	6	1	0	0	0	1	0	0	8
WSl-rep 1	2	1	0	1	0	2	0	2	8
WSl-rep 2	2	0	0	0	0	2	1	2	7
DSl-rep 1	1	0	0	2	0	1	0	2	6
No-Alfalfa 1	3	2	0	0	3	3	3	0	14
No-Alfalfa 2	6	0	0	2	1	7	0	0	16
TOTAL	61	24	6	12	4	39	4	10	

UnD. = 'undifferentiated', i.e., no record made of whether roots were live or decayed.
Krot. = Krotovina (filled-in animal burrow).

Table 2-4. Bromide distribution in the profiles of two no-alfalfa plots that received bromide in addition to blue dye during dye application. Bromide concentrations (g g^{-1} soil) were determined from soil extracts of undisturbed soil cores. These were converted into bromide concentrations in the soil solution (mg L^{-1} soil solution) using measured bulk density and volumetric water contents determined from the same cores.

Profile Face	Depth	Bromide Concentration in Soil Solution (mg L^{-1}) Horizontal Location (cm) 10	20	30	40	50	60	70	80	90	Mean	SD
	cm											
1F-60†												
	25	-	62.1	-	-	66.0	-	-	65.2	-	64.4	2.1
	45	58.2	60.6	63.0	53.6	71.4	80.3	57.7	66.4	35.7	60.8	12.4
	55	46.2	50.9	53.7	38	48.7	65.5	56.8	51.2	33.7	49.4	9.5
	65	50.6	61.1	64.9	52.5	50.2	72.0	57.0	44.2	28.6	53.4	12.6
2f-40												
	22	76.0	78.9	72.4	77.4	76.6	72.4	79.7	71.3	77.1	75.8	3.0
	40	68.2	58.1	70.9	78.4	87.2	93.3	90.0	74.0	49.1	74.4	4.7
	50	70.0	44.5	53.3	70.1	60.6	78.5	87.0	62.3	40.7	63.0	15.2
	60	67.0	37.7	44.7	64.7	61.6	67.0	79.7	49.5	41.3	57.0	14.2
	70	68.2	40.3	31.9	54.4	55.9	61.2	56.6	32.1	38.8	48.8	13.3
	80	37.6	34.8	21.8	37.8	84.0	78.4	66.9	26.7	30.2	46.5	23.5

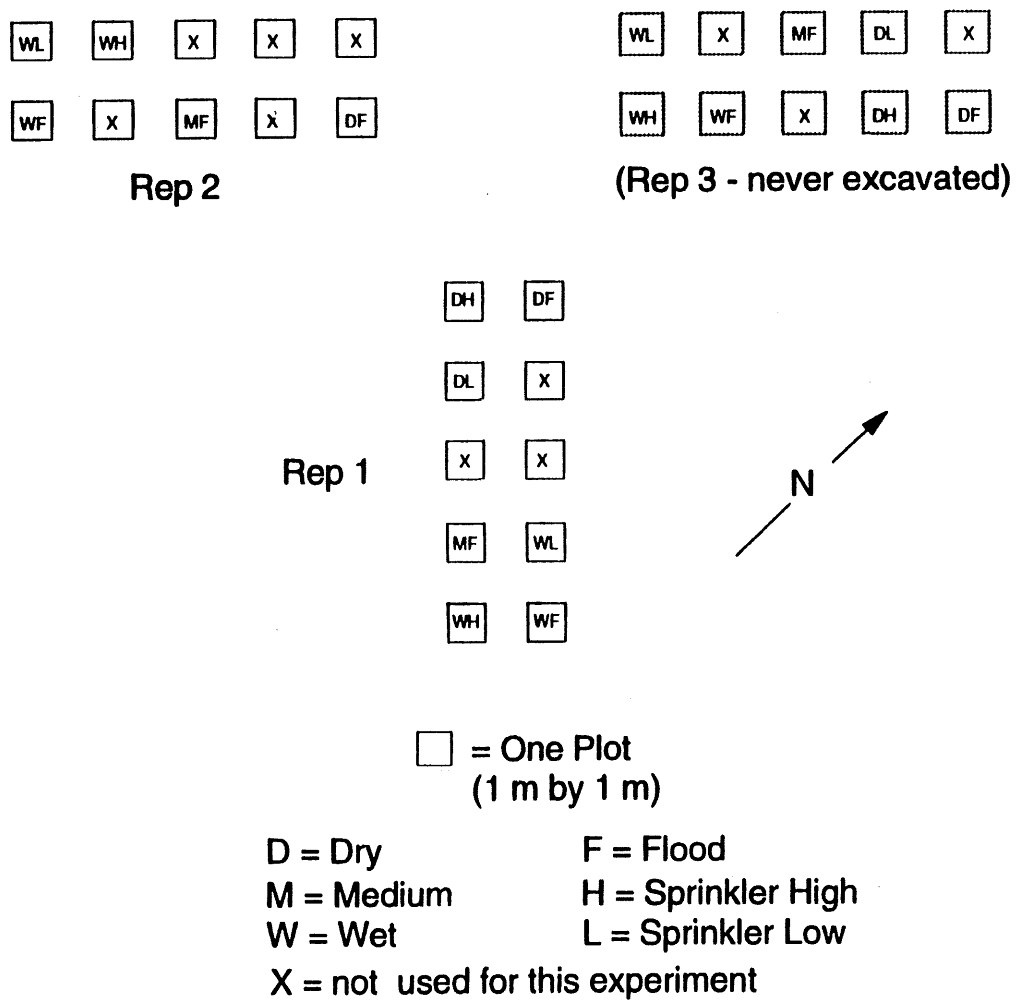


Fig. 2-1. Field layout of experimental plots.

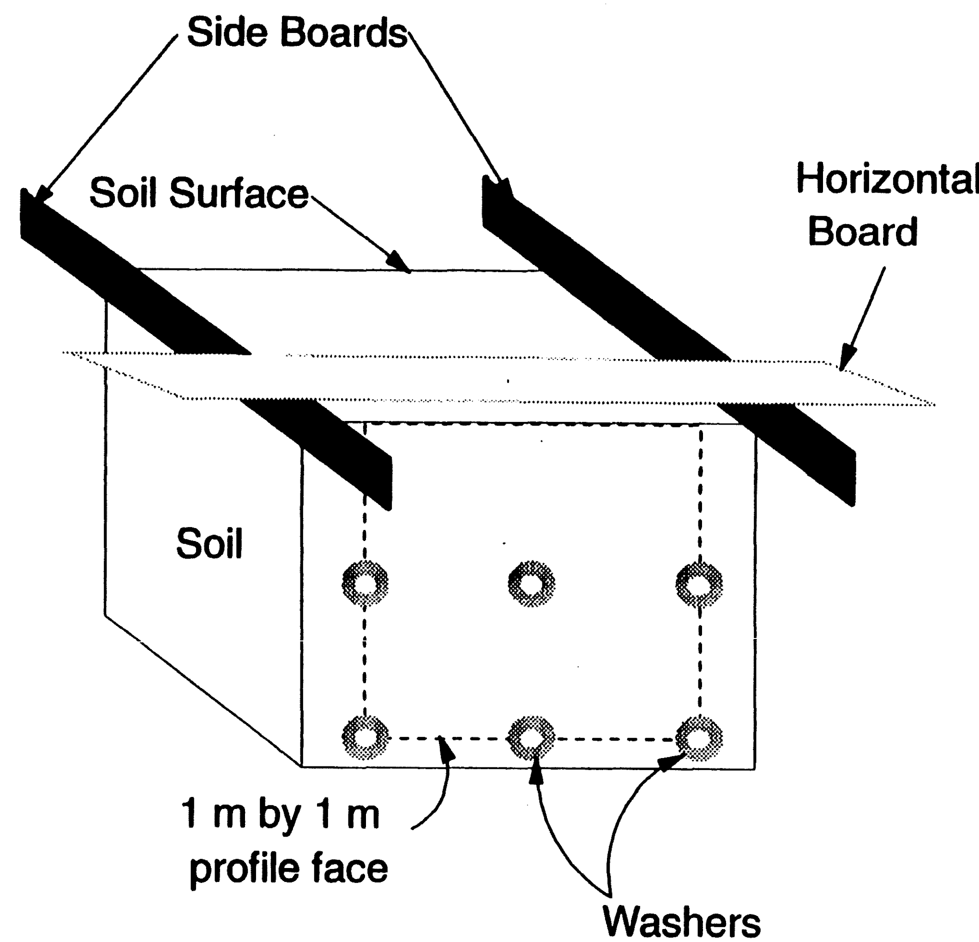


Fig. 2-2. Individual plot setup, showing board-and-washer arrangement used to maintain the spatial coordinate system and to ensure true vertical profile faces.

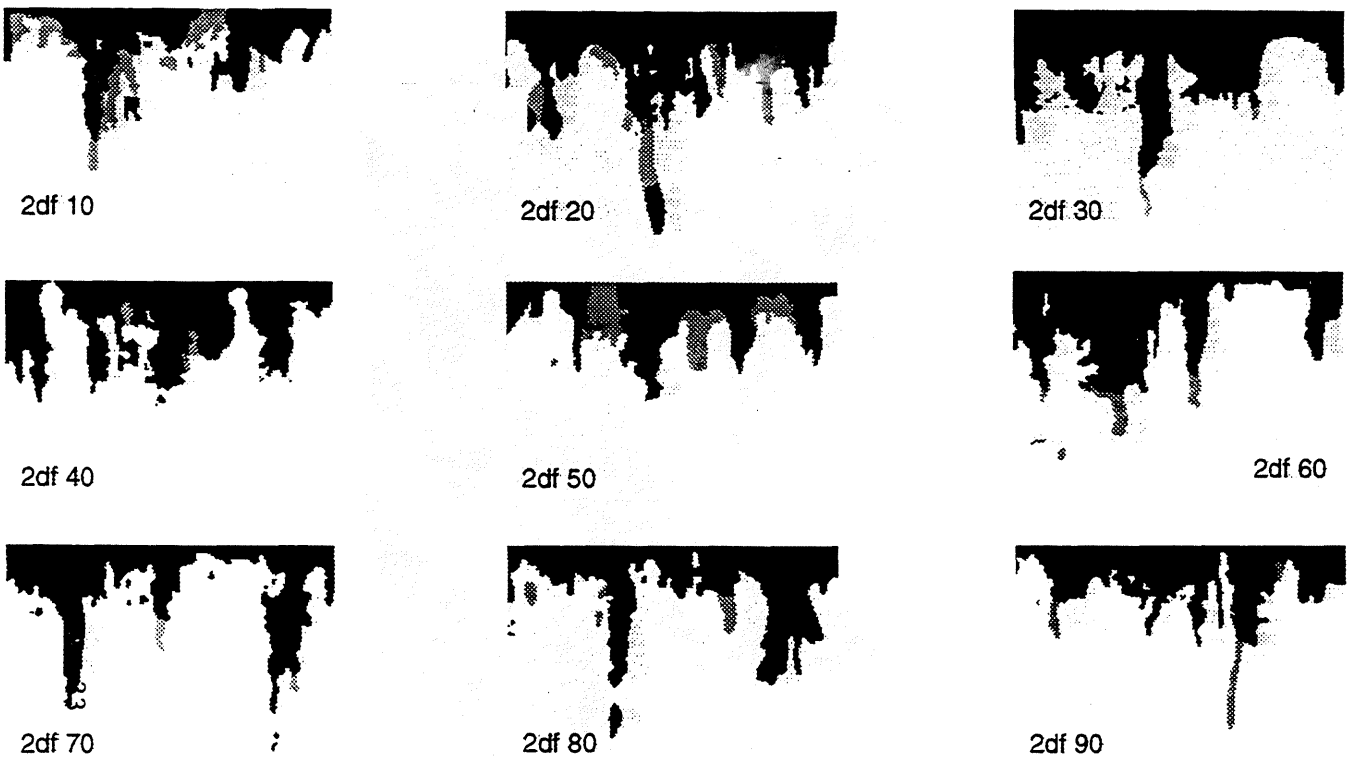


Fig. 2-3. Example of typical dye patterns seen under FLOOD application. Black areas are dyed areas, the medium grey areas are areas that were only slightly colored by the dye (i.e., pale), and the very light grey background shows the 1 m wide profile face. The top of each profile shown is 25 cm below the soil surface (approximatley at the Ap-Bt horizon boundary). These nine profiles came from the second replication of the DRY, FLOOD treatment. The number on each profile refers to distance into the plot in centimeters.

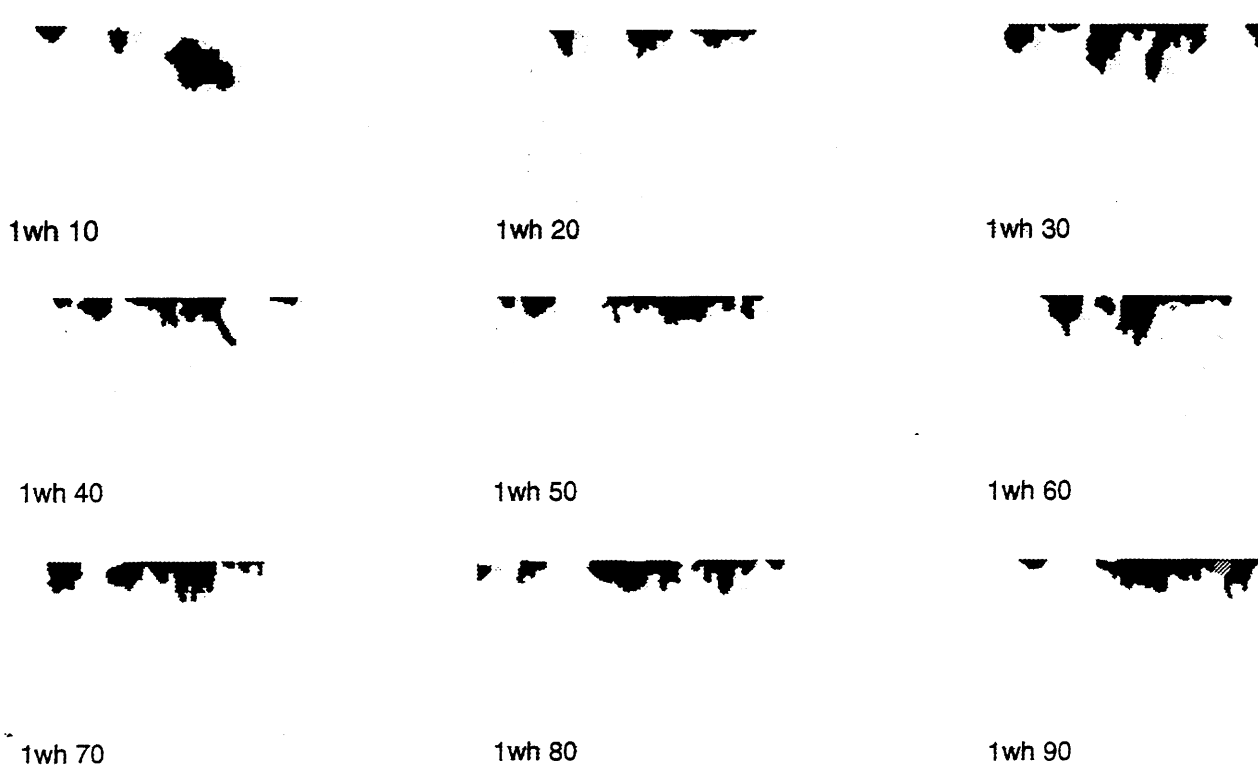


Fig. 2-4. Example of typical dye patterns seen under SPRINKLER application. Black areas are dyed areas, the medium grey areas are areas that were only slightly colored by the dye (i.e., pale), and the lvery light grey background shows the 1 m wide profile face. The top of each profile shown is 25 cm below the soil surface (approximatley at the Ap-Bt horizon boundary). These nine profiles came from the first replication of the WET, SPRINKLER-High (WH) treatment. The number on each profile refers to distance into the plot in centimeters.

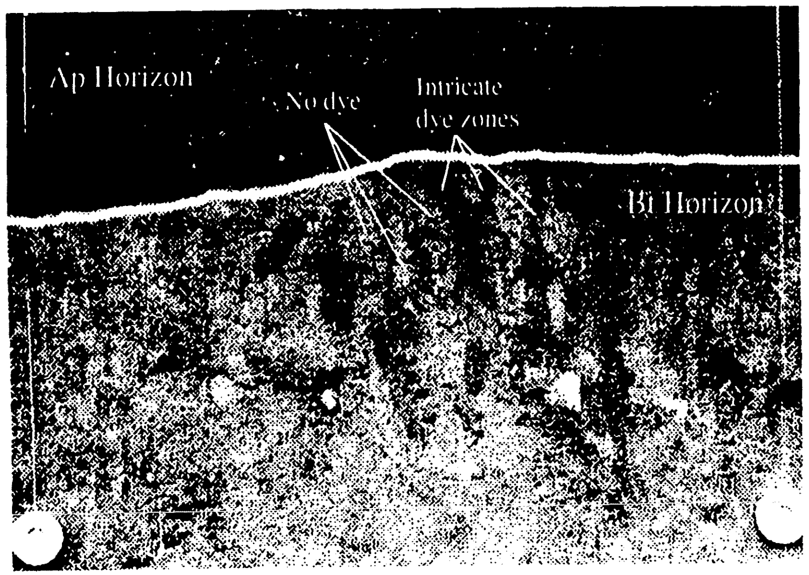
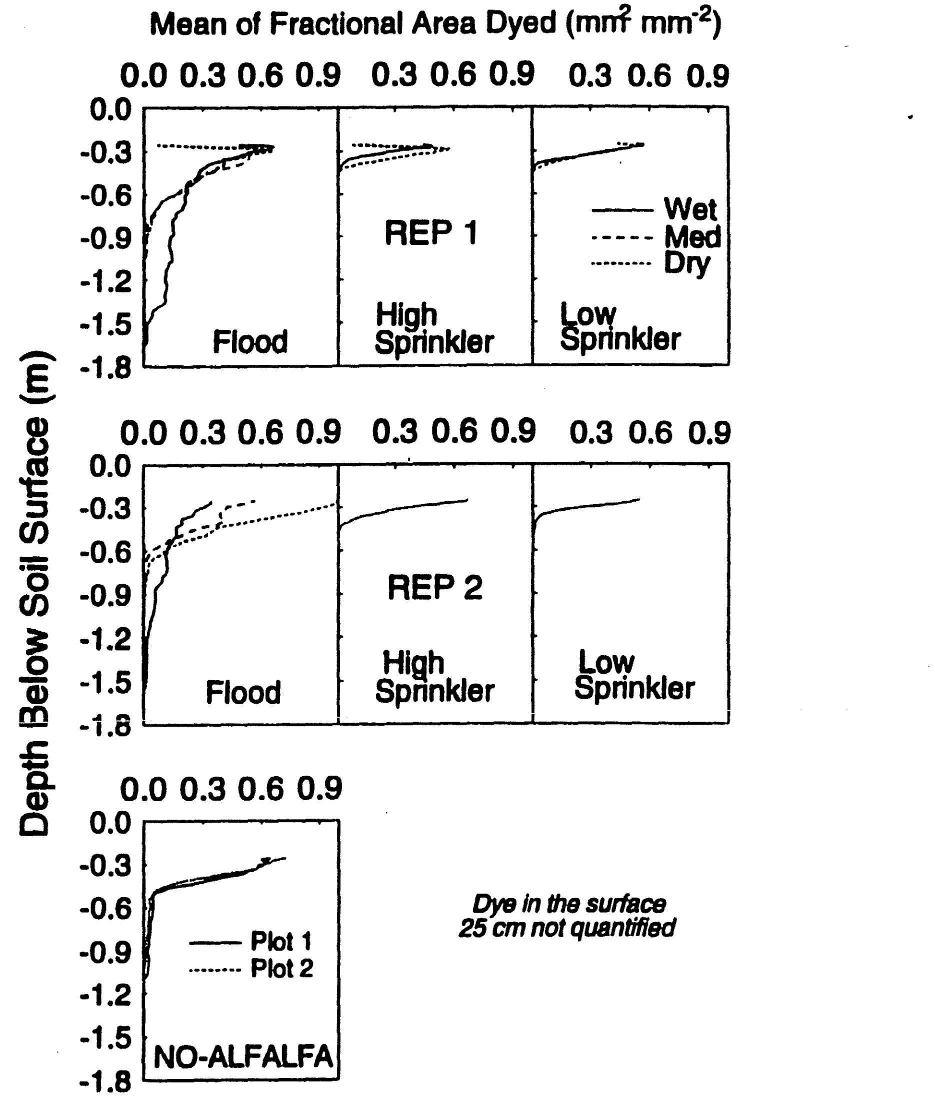
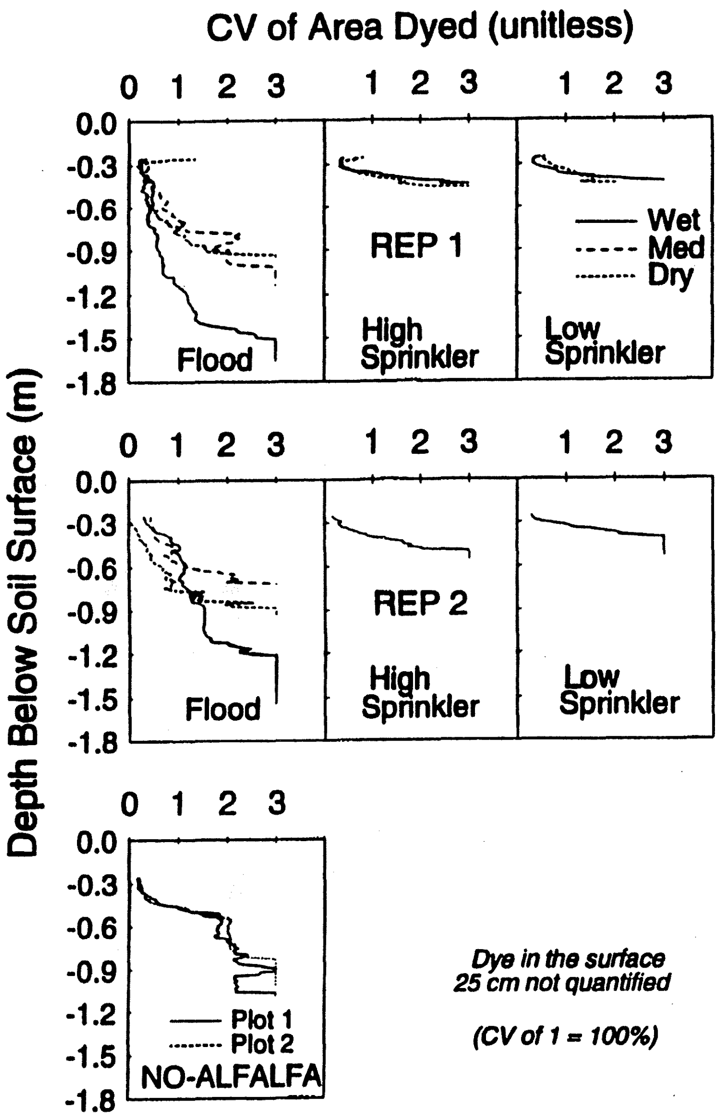


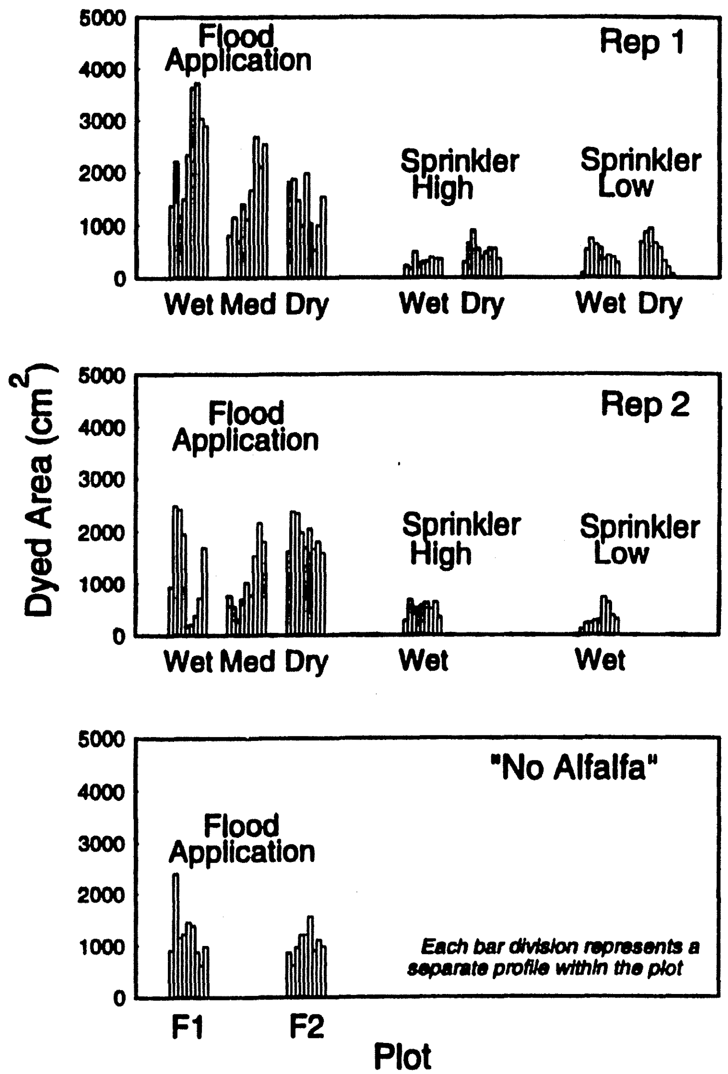
Fig. 2-5. Example of the intricate patterns of dyed and undyed zones within the soil. The distance between the two washers at the bottom of the figure are 50 cm apart. This figure has been converted from a color slide.



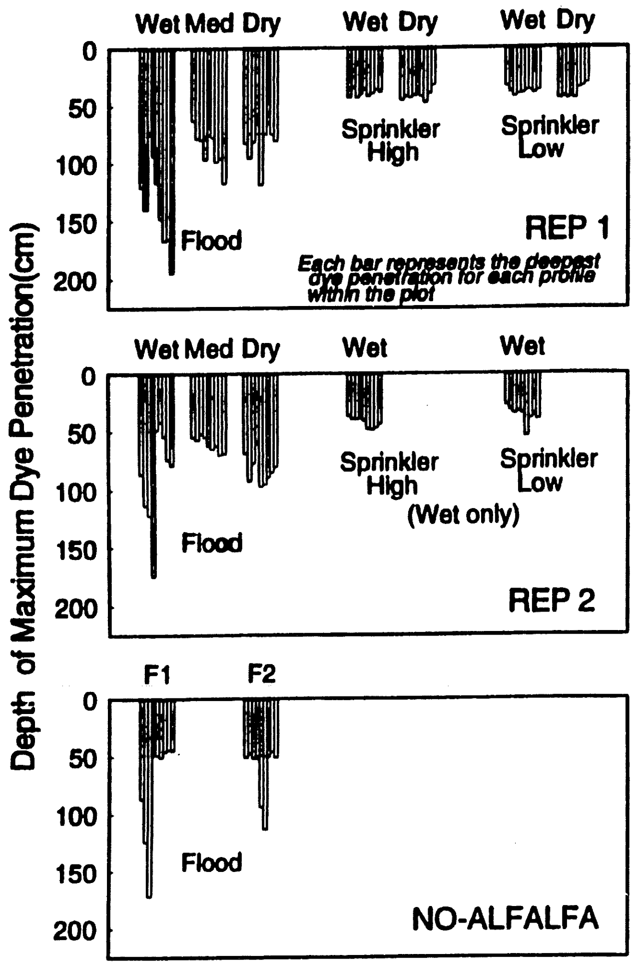
2-6. Patterns in fractional dye coverage of the profile with depth, expressed as the mean (of the nine profiles in each plot) of the fractional area dyed for each depth.



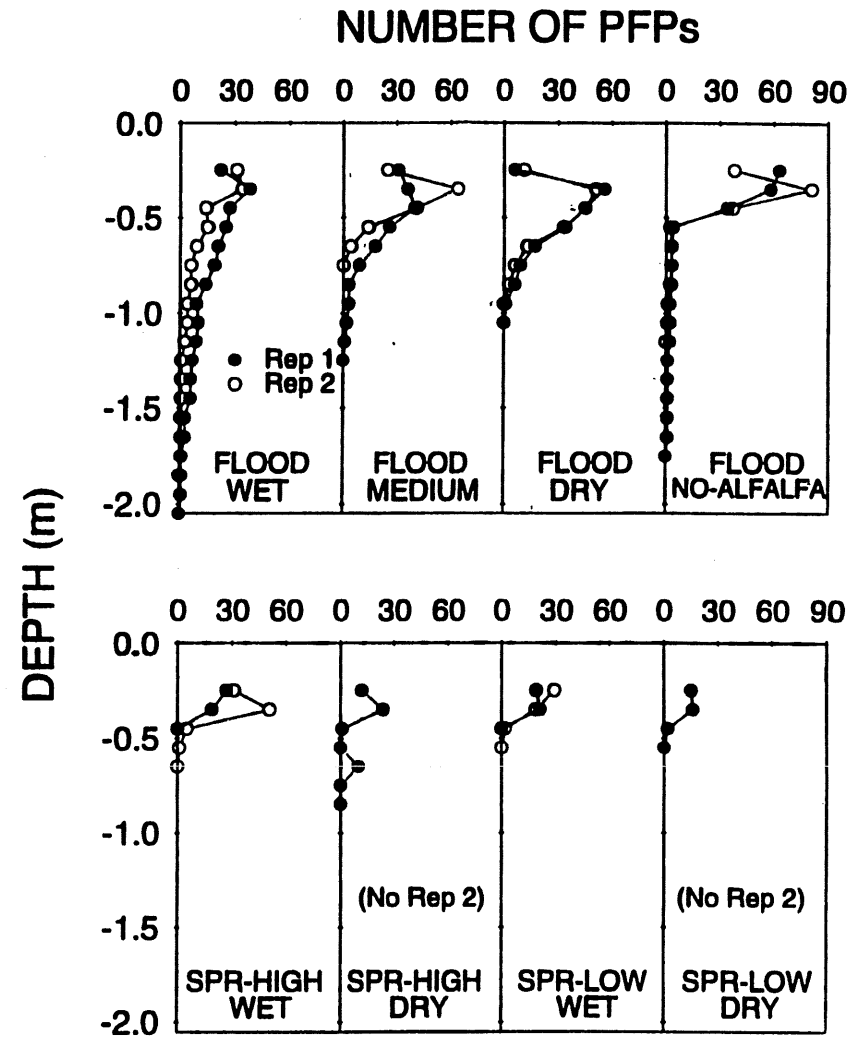
2-7. Patterns in the variability in the fractional dye coverage of the profile with depth, expressed as the Coefficient of Variation (CV) of (of the nine profiles in each plot)of the dyed area for each depth.



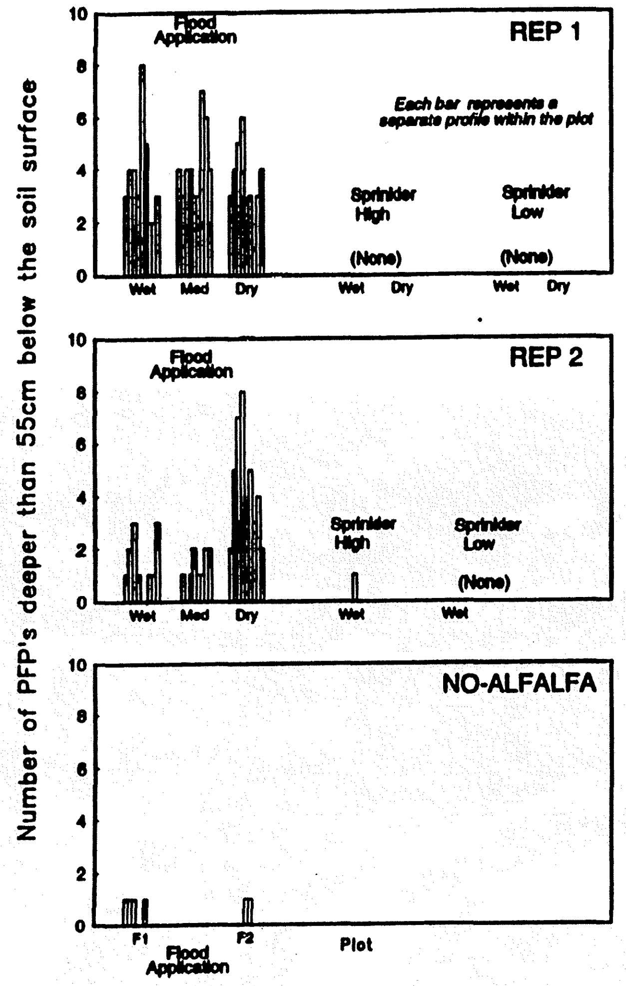
2-8. Total area dyed for each profile within each plot. Each bar represents an individual profile face within the plot (nine profiles per plot).



2-9. Depth of maximum dye penetration for each profile within each plot. Each bar represents the deepest extent of dye movement observed for a profile face (nine profile- - plot).



2-10. Pattern in the number of separate dye paths (PFPs) present at each depth for each treatment. Points shown for each treatment and replicate are the sum of the nur- - of PFPs for the entire plot (i.e., nine profiles per plot)



2-11. **The number of separate dye paths (PFPs) seen below 55 cm for each plot. Each bar division represents the number of PFPs for an individual profile face (nine profiles per plot).**

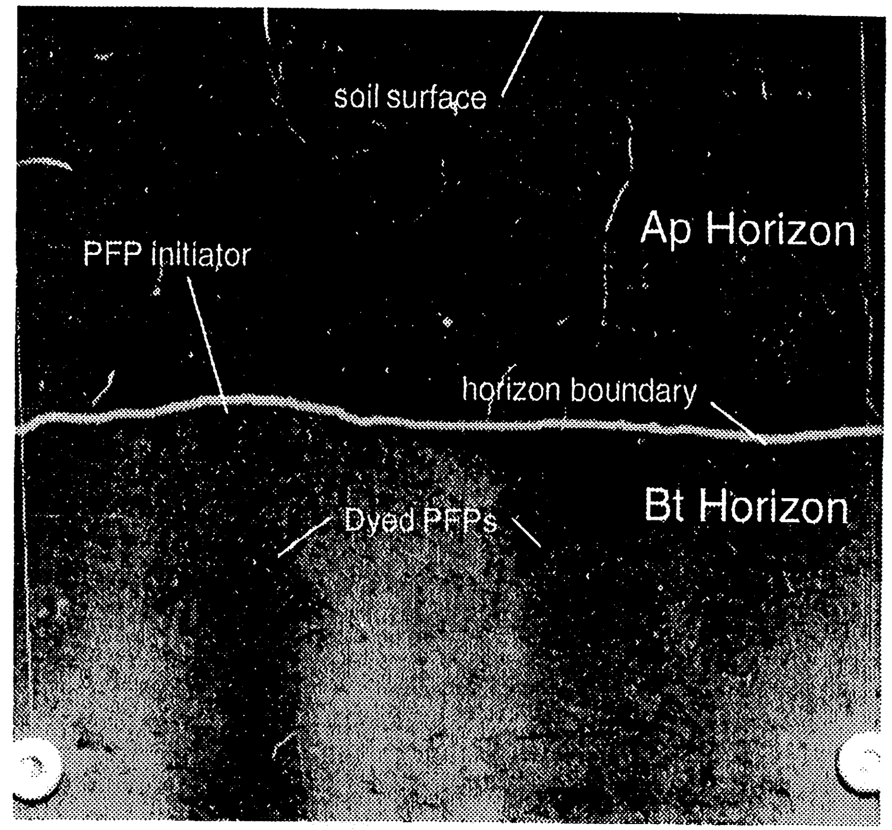


Fig. 2-12. Example of a preferential flow path (PFP) initiator as seen in the field. This image has been converted from a color slide. Within the Bt horizon the darker areas are dyed., and the lighter areas are undyed. Most of the Ap horizon in this image is dyed, but this is not observable from this altered image.

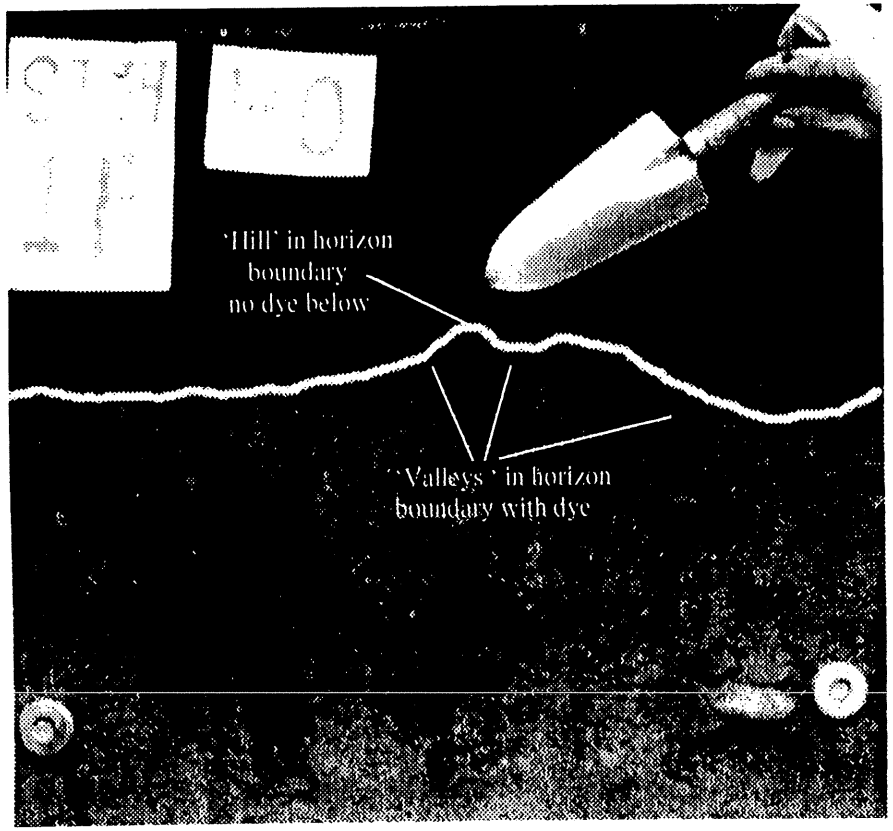
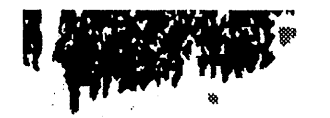
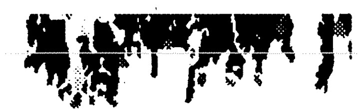


Fig. 2-13. Example of sloping horizon boundary affecting the depth of dye penetration. No dye occurs directly below the top of the hill, but dye does move into the Bt horizon at the 'toeslope' positions of the feature. The distance between the two washers at the bottom of the figure is 50 cm. The soil surface is at the top of the figure, and the horizon boundary shown is the Ap-Bt boundary. This image has been converted from a color slide.



a) F1-60



b) F2-40

Fig 2-14. Distribution of dye in two no-alfalfa plots that also received an application of bromide ion. F1 and F2 refer to the first and second no-alfalfa plots, and the numbers following indicate the profile faces at 60 and 40 cm into these two plots respectively. The dark areas are dyed, the medium gray areas are slightly dyed (i.e., pale), and the background very light grey represents the 1 m wide soil profile face. The tops of these figures start at 25 cm below the soil surface.

Chapter 3. Adsorption Characteristics of FD&C Blue #1 and Flow Velocity Effects on Dye Retardation

ABSTRACT

The objectives of this research were 1) to quantify the amount of equilibrium adsorption of FD&C Blue #1 food dye in the Ap, Bt, and C horizons of Verndale sandy loam (coarse loamy over sandy, mixed, frigid, Udic Argiborolls); and 2) to determine the relative amount of dye retardation compared to the wetting front under two different flow velocities. Twenty four hour batch equilibration measurements resulted in values for the linearized Freundlich distribution coefficient (Kd) of 4.54, 25.59, and 4.32 L kg^{-1} for the Ap, Bt, and C horizons respectively. Neither organic carbon nor clay content differences accounted for the variation. Experiments with repacked soil columns of each horizon showed that the dye is retarded relative to the wetting front, and that the extent of retardation depends on the flow velocity. In the Ap and C horizons about twice as much retardation was observed under unsaturated conditions (low flow velocity) compared to ponded conditions. Application rate had little effect on dye retardation in the Bt horizon - likely because the flow rate under ponded conditions was still very slow due to low hydraulic conductivity, thus allowing enough time to reach near-equilibrium conditions. Breakthrough curves of the dye and Br^- ion for the Ap soil showed that dye movement relative to Br^- ion is relatively slower at the lower flow velocity compared to ponded application. The occurrence of variable retardation as a function flow velocity has important implications for interpreting dye pathways as a surrogate of the pathways of water flow. In addition, knowing that there is increased adsorption in subsoil horizon(s) can further complicate the interpretation of dye patterns resulting from field experiments. Researchers using dyes as tracers of water movement need to consider these two factors when evaluating the results of studies that use dyes as tracers of water and solute movement.

INTRODUCTION

The blue food dye FD&C Blue #1 has been used by several researchers in preferential transport studies (e.g., Flury et al., 1994, Mallawatantri 1994, Andreini and Steenhuis, 1990), and it is likely that this dye will be used in the future due to its good contrast with most colors seen in soils and its low toxicity (Flury and Flühler, 1994). However, there is relatively little published literature on its adsorption characteristics in soils. Using batch equilibration studies, Flury and Flühler (1995) found linear equilibrium distribution coefficients (Kd) of 0.19, 3.00, and 5.78 dm^3 kg^{-1} for three European soils. Andreini and Steenhuis (1990) evaluated local retardation factors (R) and flow velocities for effluent collected under steady state conditions in grid lysimeters placed below large soil columns. They found local R values ranged from about 1.5 to 7, and also noted that an inverse relationship existed between the R values and the flow velocity.

In 1993 we conducted a field experiment (Chapter 2) using FD&C Blue #1 to evaluate the extent of preferential transport in Verndale sandy loam under different initial water contents and using three water application methods (flood, a high sprinkler rate, and a lower sprinkler rate). All treatments received equal amounts of dyed solution, with the time period of application varying. Examination of excavated soil profiles to which dye had been applied showed that there was much deeper penetration of the dye under flooded conditions compared to under the sprinkler conditions, and that in general there were a greater number of individual dye flow paths under flood application than under sprinkler application.

An initial interpretation would suggest that the difference in these patterns is due to greater amounts of preferential water flow under flooded conditions. An alternate possibility is that the *dye* acted differently under the two application rates due to differences in contact time with the soil, irrespective of actual differences in water flow patterns. In other words, the question raised was: Could the shallowness observed in the dye patterns observed under sprinkler conditions be due to higher adsorption at this slower application rate, as opposed to being the result of shallower water front penetration? The studies presented in this manuscript were conducted to evaluate the extent of adsorption of FD&C Blue #1 in three horizons of Verndale sandy loam, and to evaluate the effect of application rate (i.e, flow velocity) on the extent of dye retardation (due to adsorption) relative to the wetting front.

It has long been recognized that flow velocity can affect the amount of chemical adsorption on soils (e.g., Coats and Smith, 1964; van Genuchten et al., 1974). The causes of the differences in *apparent rate coefficients* (Skopp, 1986) induced by differences in flow velocity can be divided into two sets of processes: 1) *Chemical non-equilibrium* in which there are multiple types of reaction sites which have different reaction rates; and 2) *Physical non-equilibrium* in which transport of the chemical to the adsorption site is controlled by physical processes such as diffusion (also known as diffusion-controlled kinetics). Chemical non-equilibrium is often modeled with a 'two-site' approach where some of the sites have instantaneous equilibrium, and at other sites the rate of the adsorption reactions is slower. Physical non-equilibrium is often modeled using a 'two-region' approach where one portion of sites are within the realm of 'mobile water' while the other sites are in regions of relatively 'immobile water'. Either type of process, or both, may contribute to non-equilibrium conditions and observed flow velocity effects on the macroscopic scale. These effects have been observed in many studies, and much effort has gone into developing a conceptual framework for understanding and modeling non-equilibrium conditions during transport (e.g., van Genuchten et al., 1974; Skopp and Warrick, 1974; Selim et al, 1976; Cameron and Klute, 1977;, Rao et al., 1979; Nkedi-Kizza, 1984). A comprehensive review of the concepts and approaches for non-equilibrium conditions is given by Brusseau and Rao

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Numerous studies have been conducted using dyes to mark the pathways and extent of water movement through soils. Cognizant recognition is given to the different amounts of adsorption expected from different dyes. Methylene blue is expected to be quickly and strongly adsorbed due to its cationic characters. It has therefore been used to evaluate which pathways have fast water movement such that there is little time for adsorption to occur, e.g., flow through macropores such as structural voids or earthworm burrows (Bouma et al., 1977). In other studies, researchers have been more interested in overall patterns of water movement and have used dyes expected to have the least adsorption, i.e., the least retardation relative to the wetting front. These include fluorescein (e.g., Smart and Laidlaw, 1977), pyranine (e.g., Omoti and Wild, 1979; Smart and Laidlaw, 1977), Lissamine Yellow FF (Trudgill, 1987),and Rhodamine WT (Smart and Laidlaw, 1977; Kung, 1990). In fact, Rhodamine WT was developed specifically as an adsorption-resistant trace (Smart and Laidlaw, 1977). Other reasons for selecting a specific dye include detectability at low concentrations (Smart and Laidlaw, 1977), stability in the soil environment (Omoti and Wild, 1979) good contrast with soil (Mallawatantri, 1994), or low toxicity (Flury et al., 1994). The choice of FD&C Blue #1 for our field experiment was based on good contrast with our soil, low toxicity implied by its food dye designation, and results of preliminary studies using packed columns and ponded conditions which showed faster movement through the Ap horizon of our field soil compared to Rhodamine WT.

This manuscript presents the results of laboratory experiments designed to measure equilibrium adsorption characteristics and to evaluate the amount of dye retardation relative to the wetting front in our soil. The specific objectives of these studies were:

1) To determine the extent of FD&C Blue #1 food dye adsorption in the Ap, Bt, and C horizons of Verndale sandy loam; and
2) To determine whether or not the dye application rates used in our field experiment (i.e., the time periods over which dye was applied) affected the amount of dye retardation.

To meet our first objective, we conducted batch equilibration studies to determine equilibrium adsorption isotherms. For the second objective, we conducted column studies with solution application rates comparable to the field experiment conditions.

METHODS AND MATERIALS

Dye Characteristics

We used food grade FD&C Blue #1 (shipped as water-soluble powder) obtained from the Warner-Jenkinson Company, Inc., St. Louis, Missouri. *(Identification of company or brand names do not constitute endorsements but are included to provide a more descriptive listing of materials.)* This dye is also known as C.I. Food Blue 2, and as Brilliant Blue FCF (Disodium salt of ethyl [4-[*p*[ethyl (*m*-sulfobenzyl)amino]-*a*-(*o*-sulfophenyl)benzylidene]-2, 5-cyclohexadien-1-ylidene] (*m*-sulfobenzyl) ammonium hydroxide inner salt). The dye is classified as non-hazardous, and is in fact certified Kosher. Lot analysis showed 89% pure dye, with moisture, salt, and subsidiary dyes making up most of the rest. Dye concentrations reported here are in terms of dye as is - i.e., without corrections for impurities. It is non-fluorescent and has pKa of 5.8 and 6.58, meaning two of its functional groups act as anions above these pH values. Further characteristics of the dye are given by Flury and Flühler (1995). Preliminary laboratory work with saturated columns showed that it moved through the Ap horizon of Verndale sandy loam more quickly than Rhodamine WT.

Soil Characteristics

The soil used in this set of experiments was Verndale sandy loam. General properties of this series are given in Table 2-1.

Equipment and Settings

Dye concentrations in solution were determined by measuring absorbance at 630 nm using a UV/Visible spectrophotometer. Most samples were run using a Varian DMS 200 model, while a Milton Ray Spectronic 20D was used for the second replicate of the 3 h shaking, and both replicates of the 72 h shaking time. The Milton Ray had a slightly narrower detection range which means there was less precision at low concentrations and that the highest concentration samples required dilutions to be read.

Conversion from absorbance to concentration was made using a least-squares regression for a series of standards of known concentration. The detectable concentration range on the Varian spectrophotometer was 0.2 to 20 mg L^{-1}. The reciprocating shaker used in this experiment had total horizontal displacement of 4 cm and the rate of movement was approximately 3 strokes per second. Equilibration temperature was monitored using thermocouples placed between tubes in the center of each rack. Solution pH was determined using a 'combination' pH electrode. Centrifugation was conducted with a Juoan C412 benchtop centrifuge, at 4000 rpm. At this speed, the time needed to remove particles smaller than 0.1 µm was 10 min using the following equation (Roy et al., 1987):

$$t = \frac{3.71 x 10^{9}}{v^{2}} \ln\left(\frac{R_{b}}{R_{t}}\right) \tag{1}$$

where:
t = time (min),
v = revolutions per minute,
R_b = distance from center of rotor to bottom of centrifuge tube, and
R_t = distance from center of rotor to top of liquid in the tube.

Adsorption Isotherms

Adsorption isotherms were measured for the Ap, Bt, and C horizons of Verndale sandy loam. Sieved (< 2 mm), moist soil (0.09, 0.05, and 0.02 g g^{-1} respectively) was used for these experiments. Unless otherwise noted, 'dye solution' refers to a 0.005*M* $CaCl_2$ solution containing dye (at various concentrations). The $CaCl_2$ was added as a background electrolyte to ensure that all samples were at about the same ionic strength, and to help flocculate suspended material that would interfere with the spectrophotometer readings. Molarity of 0.005*M* was chosen as being similar to the soil solution molarity expected in a sandy soil (P.Bloom, personal communication 1994).

Soil:Solution Ratio Determination

To select an appropriate soil:solution ratio we used the criteria that the fraction of the initial chemical which remained in solution after equilibration was between 0.20 and 0.80 (McCall, 1980). This range is specified so that there is adequate precision when determining solution and adsorbed concentrations. In order to determine this ratio, five soil:solution ratios - spanning the range suggested by Roy et al. (1987) - were evaluated for each soil horizon by using variable soil mass with a constant solution volume. These ratios were 1:4, 1:10, 1:20, 1:100, and 1:500. The moist equivalent of 5.00, 2.00, 1.00, 0.10 or 0.04 g oven-dry soil (± 1%) was weighed into 30 ml plastic tubes, to which 20 ml of a 10 mg l^{-1} dye solution prepared in 0.005 *M* $CaCl_2$ was added. The tubes were then capped and shaken for 24 hours, and centrifuged for 15 min. The supernatant was then transferred to clean plastic tubes prior to absorbance measurements. A ratio of 1:10 was found to be most appropriate for the three horizons (see *Results and Discussion*) and was therefore used for the remaining equilibration experiments (next section).

Equilibration Time and Isotherms

Soil (2.00±0.02 g oven-dry basis) was weighed into plastic tubes. A 20 ml aliquot of dye solution was then added to each tube in concentrations of 1, 3, 5, 10, or 20 mg l^{-1}. Dye-blanks (5 mg l^{-1} dye solution, with no soil) and soil-blanks (soil with 0.005*M* $CaCl_2$ only) were also prepared for each batch of samples. The dye-blanks were used to determine the amount of dye loss during the procedure from photodegradation, volatilization, adsorption to equipment, etc. The soil-blanks were used to determine background soil absorbance. Tubes were capped and placed on a reciprocating shaker for 1, 3, 24, 48, or 72 hours. After shaking for the appropriate time, tubes were centrifuged for 15 min, and the supernatant transferred to clean tubes for absorbance measurement, and subsequent pH measurement. All treatments were replicated twice.

The difference between initial dye concentration and dye concentration measured following shaking with soil was attributed solely to sorption of the dye on the soil. It is possible that some biological dye degradation occurred that was not measured in the soil blanks. We made no attempt to measure dye degradation, or to compare adsorption on sterilized soils. Least-squares regressions between solution and calculated adsorbed concentrations were made for each combination of soil horizon and shaking time. Three sets of regressions were run in order to evaluate the appropriateness of three adsorption models: 1) Nonlinear Freundlich model using log transforms of the adsorbed and solution concentrations to determine the coefficients K_f and *1/n*:

$$C_a = K_f C_s^{(1/n)} \tag{2}$$

where C_a = adsorbed concentration (mg kg^{-1}), and
C_s is the solution concentration (mg L^{-1});

2) Linearized Freundlich model using untransformed data to determine the linearized coefficient K_d in:

$$C_a = K_d C_s \tag{3}$$

and 3) Langmuir isotherm model with coefficients K_L and M given in:

$$C_a = \frac{K_L M C_s}{1 + K_L C_s} \tag{4}$$

where the 1/M is the slope of the linear regression between C_s/C_a and C_s, and $1/K_LM$ is the intercept.

Comparison with using procedure of Flury and Flühler (1995)

We also wanted to compare the results of our adsorption isotherm experiments with those of Flury and Flühler (1995). However their equilibration procedures were slightly different from ours, so we ran two replicates of each horizon under conditions reported by Flury and Flühler (1995). These authors used a 3-hour shaking time, 1:1.5 soil:solution ratio, and a 0.01*M* (compared to our 0.005*M*) $CaCl_2$ background electrolyte solution. To meet our equipment constraints we used 10 g soil plus 15 ml solution rather than the 20 g soil and 30 ml solution used by these authors.

Effects of Application Rate on Dye Retardation

Wetting Front Advance Measurements

Clear plastic columns (51 mm inner diameter by 250 mm long) were packed with moist soil (0.07, 0.05, 0.02 g g^{-1} for Ap, Bt, and C horizon, respectively) to bulk densities of 1.51, 1.58 or 1.52 Mg m^{-3}. Dye solution containing 100 mg L^{-1} blue dye plus 100 mg L^{-1} KBr dissolved in 0.005*M* $CaSO_4$ was added to the columns at one of two rates designed to mimic the field application rates of FLOOD and SPRINKLER-HIGH (Chapter 2). Columns receiving the FLOOD rate received 130 mm solution (265 ml) instantaneously so that the surface was ponded, while the SPRINKLER-HIGH rate was approximated by an INTERMITTENT laboratory treatment which consisted of hourly aliquots of 7.3 mm (15 ml) using a burette. As in the field study, additions in the INTERMITTENT treatment occurred over two days with no application overnight. Between dye additions, a moist paper towel was loosely placed above the soil surface in the column to minimize evaporation. The columns were open to atmospheric pressure at the top and the bottom. Each treatment was replicated three times for the Ap horizon, and two times for the Bt and C horizons.

During the infiltration of the dye into the columns, the distances from the surface to both the wetting front and the dye front were recorded as a function of time. The distance each front moved at specific times allowed calculations of a retardation factor *(R')* which describes how slowly a chemical moves compared to the wetting front as result of chemical sorption. For a given time ***t*** :

$$R' = \frac{V_{H_2O}}{V_{dye}} = \frac{L_{H_2O}}{t} * \frac{t}{L_{dye}} = \frac{L_{H_2O}}{L_{dye}} \tag{5}$$

where: V = velocity
L = distance into column.

The retardation factor R' described in Eq. (5) is similar to the more specific retardation coefficient (R) given in Eq. 6 which is often used in modeling solute transport using assumptions of steady state water flow with linear, equilibrium adsorption conditions (e.g., Davidson et al., 1968; Parker and van Genuchten 1984).

$$R = \frac{\rho_b K_d}{\theta} + 1 \tag{6}$$

where: ρ_b = soil bulk density (Mg m^{-3})
K_d = soil-chemical specific linear equilibrium adsorption partition coefficient (L kg^{-1})
θ = volumetric soil water content (m^3 m^{-3})

Breakthrough Curves

Column effluent was collected from two replicates of each dye application treatment to Ap horizon soil. The columns used for the breakthrough curves required continued additions of dye solution until several pore volumes were eluted. Column effluent was collected in units of about 15 ml throughout the entire experiment. Actual volumes of effluent were determined by weighing each tube. Dye concentrations in the effluent were quantified using the spectrophotometer, and Br^{-1} concentrations were determined using an ion specific electrode. Electrode readings were recorded after 90 sec emersion. Standards were rerun about every ten samples, and the electrode membrane was polished every thirty samples.

RESULTS

Adsorption Isotherms

Experimental conditions occurring during the isotherm experiments are listed in Table 3-2. Solution pH of the C horizon soil-blanks was slightly higher than for the Ap and Bt horizons. The pH of the dye solution was similar to the range seen in the soil blanks. Temperature fluctuations during the course of the experiment were very small. Generally, the shaking tubes were slightly warmer than ambient room temperature, in spite of foam packing placed between the tubes and the floor of the shaker (motor area). Dye-blanks (no soil) exhibited slight decreases in concentration, but since these were always within 3% of the initial concentration they were considered to be within the range of experimental error and no corrections were made to the measured adsorption data. Likewise, slight absorbance was measure in solutions from the soil-blanks (no dye), but since the corresponding calculated concentrations were at least an order of magnitude less than the lowest sample concentration in the experiment, no correction for background soil absorbance was made.

The most appropriate soil:solution ratio for all three horizons was found to be 1:10 (Table 3-3), since this ratio resulted in 20 to 80% removal of the dye initially in solution (the range suggested by McCall et al., 1980). This ratio agrees well with the initial estimate of 1:10 made using a Kd value of 3.0 L kg^{-1} from the following expression suggested by Roy et al. (1987):

$$r = \frac{M_a}{(M_{si} - M_a) * Kd} \tag{5}$$

where: r = soil:solution ratio,
M_a = mass of solute adsorbed (µg),
M_{si} = mass of solute initially present in the solution, and
Kd is the distribution coefficient (as in Equations (3) and (6)) in units of g cm^{-3}.

The Kd value of 3.0 is in the middle of the Kd range of 0.19 to 5.78 L kg^{-1} measured by Flury and Flühler (1995). A ratio of 1:4 would also have been appropriate for the Ap and C horizon, but this ratio allowed too much removal (> 80%) with Bt horizon soil. The ratio of 1:1.5 used by Flury and Flühler (1995) was not appropriate for Verndale sandy loam since removal of the dye from solution was nearly 100% with the Bt horizon, and removal for the other two horizons was at the upper end of the 20 to 80% removal range (Table 3-4).

The criteria for determining the equilibration time suggested by Roy et al. (1987) is that there is less than 5% change in solute concentration over a 24-h period. Using this criteria, we determined a shaking time of 24 hours (Table 3-5) to be appropriate our isotherm experiments. Shorter shaking times showed large changes in solution concentration between times. Longer shaking times increase the risk that a larger role is played by degradation processes not accounted for by the dye-blanks.

The values in Table 3-6 show that increased equilibration time increases calculated distribution coefficient. The fitted Kd and Kf values increase 130 to 210% as shaking time is increased from 1 h to 24 h. These differences demonstrate the importance of describing experimental conditions (e.g., shaking time) when presenting the results of batch adsorption experiments.

Values for fitted Kd, Kf, and K_L given in Table 3-6. The correlation coefficients show that the linearized and nonlinear Freundlich models fit the data better than the the Langmuir. Due to the good fit of the linearized form the simpler linear distribution coefficient (Kd) seems adequate for modeling purposes when working in the range of concentrations used in this study.

A comparison of the fitted models is shown (Fig 3-1) for three shaking times (1, 3, 24 h) selected for closer evaluation. The 24 h time is probably the most representative of 'true' equilibrium (discussed above). The 1 h time may be the most relevant for evaluating adsorption in our field study, since this soil has high permeability and it is unlikely that there was more than one hour contact time between the infiltrating dye solution and the soil in the field. Infiltration rates ranged from 65 to 360 mm h^{-1} for ponded and -35 mm tension respectively (Chapter 2). The 3 h shaking time was evaluated because this time was used by Flury and Flühler (1995) following the guidelines for testing chemicals recommended by the Organization for Economic Cooperation and Development (Guideline for testing chemicals, no. 106, OECD, Paris). While their procedure resulted in greater removal of dye from the solution by our soil (compared to our procedure), the calculated Kd and Kf values for the Ap and C horizon using this procedure are only slightly higher than the ones calculated using the 1:10 ratio procedure. There were substantial differences in the calculated value of Kd and Kf for the two procedures in the Bt horizon. This difference might in part be the result of the much higher removal of dye that occurred with the 1:1.5 soil:solution ratio, such that there was reduced accuracy in the measurement of absorbance.

With 24 h shaking (our 'equilibrium'), Kd and Kf values for the Ap and C horizons are similar to those reported by Flury and Flühler (1995) for two of the three soils they evaluated (Table 3-6). The Kd and Kf values for our Bt horizon are about ten times higher. This finding goes against the general assumption that the greatest amount of adsorption occurs in the A horizon because of its higher organic matter contents. One possibility for the difference between our results and the accepted convention is that clay content is an overriding factor. To evaluate this hypothesis, we normalized the Kd values at two equilibration times with both organic carbon and clay contents.

$$K_{oc} = \frac{Kd}{f_{oc}} \tag{6}$$

$$K_{clay} = \frac{Kd}{f_{clay}} \tag{7}$$

Where f_{oc} and f_{clay} are the fractions (weight basis) of organic carbon and clay respectively. The Kd values, and normalized values are given in Table 3-7.

The large variability in both K_{OC} and K_{clay} values for the three horizons suggests that neither organic carbon nor clay content explain the differences in adsorption coefficients between the three horizons. Flury and Flühler (1995) also found that organic carbon was not a good predictor of Kd in their soils. These results negate the conventional concept that horizons having high organic matter or high clay content will have higher adsorption capacity for FD&C Blue #1, and therefore negate the use of the generalized K_{OC} approach for estimating the extent of adsorption of this dye. Researchers working with this dye need to evaluate the extent of adsorption for each of their soils.

Effects of Application Rate on Dye Retardation

Wetting and Dye Front Advance Rates

Calculated values for retardation coefficients (*R'*) based on dye and wetting front advance rates (Eq. (5)) are listed in Table 3-8 for the Ap, Bt, and C horizons under both FLOOD and INTERMITTENT conditions. These values are given in ranges rather than single numbers because *R'* generally increased over the course of the experiment, i.e., the ratio of wetting front distance to dye front distance became greater as the fronts moved more deeply into the column (discussed in more detail below).

For the Ap and C horizons, the retardation of the dye front relative to the wetting front is two to three times higher under FLOOD conditions compared to INTERMITTENT. In other words, for the same volume of added solution, the dye front advances only about one-half as much at the lower flow rate as compared to the higher flow rate.

The Bt showed much greater retardation compared to the other two horizons - which correlates well with the higher Kd values determined in the batch experiments. There was little difference in the *R'* values resulting from the variation in application rate in the Bt horizon. The lack of an application rate effect may be because the flow velocities under both application rates were generally low under both conditions. (The average wetting front advance rates were 0.6 mm and 1 to 4 mm min^{-1} for INTERMITTENT and FLOOD conditions respectively.) Consequently, there was more time for dye to interact with the soil compared to the other horizons, i.e., approach equilibrium conditions. It might also be that the greater amount of adsorption (as seen in the higher Kd value) in the Bt compared to the Ap and C horizons outweighs the role of flow rate. In other words, the high amount of adsorption in the Bt overwhelms the effects of flow velocity, such that flow rate and contact time have less of an influence on retardation in this horizon.

The C horizon appears to have slightly higher retardation under INTERMITTENT conditions compared to the Ap, despite the finding of similar Kd values in the batch experiment results do not support this. One possible explanation is that the higher *R'* may be the result of generally lower water content in the C compared to the Ap under INTERMITTENT. There should be an inverse relationship between water content (θ) and *R'* similar to that shown for *R* in Eq. (6), even under the non-steady state conditions of *R'* determination.

Table 3-9 lists the *R'* values and the distance the dye and wetting fronts moved as a function of time. In general there is an increase in *R'* as time increased. This is at least partially explained by the increased difficulty in seeing the dye front at later times since dispersion caused it to be less distinct. It was the leading edge of the dye and wetting fronts that were observed and recorded, and the distance between this front and the center of mass increased over time due to dispersion. Consequently, the retardation values calculated are higher compared to if concentrations or centers of mass had been used, and these increases are greater at longer times.

Breakthrough Curves

Dye concentrations in column effluent from Ap soil for INTERMITTENT and FLOOD applications show distinctly different patterns (Fig. 3-2). It took about twice the effluent volume under INTERMITTENT application to reach the relative concentration (C/C_0) of 0.50 compared to under FLOOD application. The cumulative volume that have been eluted when C/C_0 reaches 0.50 corresponds to the time at which the solute front would be expected to arrive in the absence of dispersion - i.e., a sharp wetting front. This crude estimate of twice the retardation of dye at the lower flow velocity supports the results obtained with the wetting front advance analysis. Bromide effluent curves between the two application treatments showed little difference from each other. Presentation of the dye breakthrough curves for the two replicates show that between-treatment differences are much greater than within-treatment variation.

Observed differences in effluent curves between the two flow rates supports both the mobile/immobile water concept (physical controls on adsorption), and the concept of multiple reaction sites where slow reaction kinetics controls adsorption on some types of sites. (i.e, when the solution flows at high velocities, it is too fast for some adsorption sites to come to equilibrium). It is not possible to tell from the curves which processes are occurring. Evaluation of the differences in concentration of Br^- at C/Co = 0.5 between the two treatments shows there is a relative delay in Br^- breakthrough under INTERMITTENT conditions compared to FLOOD. This observation suggests that physical processes play at least some role since the bromide is not expected to interact at multiple types of reaction sites the way the dye might.

(Some comments are necessary to explain the pattern of the bromide effluent curves. I explain this in detail because it has been difficult for people to grasp in conversations about the data. Understanding of these curves hinges on the fact that these columns were not run at steady state conditions. Therefore effluent volume does not correspond to volume input at a given time. Bromide elutes nearly instantaneously - which we expect since it should have little interaction with the soil due to its anionic nature, and since there was little water present in the column initially to be displaced. Therefore some of the input solution is expected to elute within the first few aliquots of effluent collected. Hence the appearance of a non-adsorbing solute in the initial effluent samples. This process may have been enhanced if anion exclusion were present such that Br^- moved faster then the infiltrating front.)

When these breakthrough curves are evaluated as a function of time since initial dye addition (Fig 3-3), one difference is apparent between the bromide and the dye under flood conditions. During the overnight periods when solution was not added, the dye concentration in the subsequent effluent samples tended to be lower, while concentration of Br^- remained the same.

This suggests that perhaps there is some degradation of the dye in the column overnight. (The same pattern of decreases in dye concentrations after each overnight period is observed for dye in the INTERMITTENT conditions. Unfortunately Br^{-1} readings were measured for only every fifth sample once concentrations of $C/C_0 = 1.0$ were clearly established. Therefore we can not see whether or not Br^{-1} followed the same pattern as under FLOOD conditions (i.e.,no decrease).) If it were totally due to physical non-equilibrium processes (i.e., water diffusing into less accessible pores, so that dye concentration in the more mobile water decreased), we would expect to have seen similar decreases in Br^- too. The absence of such decreases in Br^- concentration suggest processes such as chemical non-equilibrium or degradation of the dye were occurring.

The observation that flow velocity affects dye retardation is somewhat qualitative, but demonstrate the occurrence nonetheless. Andreini and Steenhuis (1990) discussed a similar finding with this dye. That retardation is a function of flow velocity suggests that flow velocity strongly influence dye patterns in a soil, and this must be taken into account when interpreting dye movement as a surrogate for water movement. It also seems likely that there may be similar problems when dye paths are used to make generalizations about the movement of sorbing chemicals (e.g., dye patterns extrapolated to patterns of pesticide transport), since chemical interactions of a different specific chemicals with a given soil may be different. For example we have demonstrated that neither organic carbon nor clay content alone can explain the adsorption of the dye - while many organic chemicals of concern are more readily adaptable to the K_{OC} approach.

SUMMARY AND CONCLUSIONS

This paper reports the results of batch equilibration and columns leaching studies on the adsorption of the blue dye on three horizons of the Verndale sandy loam. There were only slight differences between the linearized and nonlinear Freundlich adsorption models, and both described the data well.

The Kd values of the Ap and C horizons were in the same range as the Kd values reported by Flury and Flühler (1995) for two of their soils (about 3 to 5 L kg^{-1}). Our Bt horizon had a Kd value about 10 times higher than these, thereby indicating greater adsorption of the dye in this horizon. Organic carbon content does not appear to govern adsorption (i.e., K_{oc} values were highly variable), as was also observed by Flury and Flühler (1995). Clay also did not explain the variations in adsorption between the argillic Bt horizon and the other horizons. We found that shaking time during the equilibration had a large affect on the Kd and Kf values - with an increase of 130-210% as shaking time increased from 1 to 24 h. This indicates that equilibrium with FD&C Blue #1 in Verndale sandy loam is not quickly reached, even under the ideal mixing conditions of large amounts of solution relative to soil in a well-mixed environment. This suggests that in the field, equilibrium between the dye and the Verndale soil is rarely, if ever, reached.

Simple comparisons of the distance the dye and water fronts moved at a given time in Ap, Bt, and C horizons showed that the dye was retarded by about 2, 8, and 3 times more, respectively, for INTERMITTENT (low velocity) application compared to FLOOD conditions (high velocity). Evaluations of breakthrough curves of the dye and the conservative tracer bromide in the Ap horizon soil also suggested twice the retardation for the lower flow rate.

Several implications can be taken from these results. First, interpretations of dye patterns in the field need to consider variation in *chemical* as well as physical conditions when interpreting dye flow pathways. For example, patterns attributed to changes in soil physical properties (e.g., less movement into areas with finer soil texture) may be due as much to increased adsorption by this material, as to decreased permeability. For example, if there were a fairly uniform wetting front and the dye moves less deeply in zones with higher Kd values, the irregularity of the resulting dye front would be exaggerated compared to the pattern the wetting front.

Second, the qualitative differences observed in dye retardation between the two flow rates in our column experiments demonstrate that equilibrium conditions are not obtained under the FLOOD conditions, and perhaps not even at the INTERMITTENT application rate used. (This could be evaluated by using a third, lower flow rate.) This lack of equilibrium may be due to chemical and/or physical non-equilibrium processes. Our procedure can not distinguish between these.

Third, given the relatively high Kd values obtained in the batch equilibration experiments, it appears that any deep movement of the dye observed in the Verndale soil in our field experiment (Chapter 2) can only be due to conditions of very rapid movement. This is particularly true in the Bt horizon, since the 1-h shaking time Kd was almost 20 L kg^{-1}. Any deep movement through the Bt horizon must have occurred very quickly with little contact with the matrix,

FUTURE RESEARCH

1) *Evaluate the effect of flow velocity on the amount of retardation using steady state conditions.*
The column experiments presented in this paper were designed to answer qualitative questions with respect to our field experiment, namely does application rate effect the amount retardation? However, these experiments do not allow more traditional quantitative analysis of the retardation rates because of the transient conditions, and in fact can not be analyzed using any existing models of solute transport due to the transient experimental conditions Therefore it would be useful to determine the retardation coefficient R at steady state conditions approximating the average flow rates of the FLOOD and INTERMITTENT conditions reported here. Another benefit for doing the steady state experiments is to more easily convey the results to other researchers. It has proved very difficult to convey the observation of non-equilibrium to other researchers because of the non-standard approach used.

2) Conduct additional batch experiments at higher concentrations - closer to what people have used in the field (e.g., 100 mg L^{-1}). Theoretically, the soil's capacity to adsorb a chemical is finite, and at high solution concentrations the relationship between solution and adsorbed concentrations may no longer be linear. Since higher concentrations are generally used in the field, this part of the curve is of great interest. I would suggest measuring isotherms using concentrations of ranging from 1 to 3000 mg L^{-1}, since this goes from the low end of the range detectable by the spectrophotometer to the upper limit of concentrations that are expected to be used in the field. The same procedure reported here could be use with the addition of a dilution step for all samples > 20 mg L^{-1} to keep them in range of the spectrophotometer.

3) *Additional batch and column experiments using other dyes and/or soils.*
Similar batch and column experiments with other dyes commonly used in solute transport studies (e.g., Rhodamine WT), and with other sandy soils (e.g., Hubbard sand) would determine if the occurrence of non-equilibrium processes with dyes is widespread, or only important in the combination used in my research (Verndale soil with FD&C Blue #1). Given that non-equilibrium processes have been widely reported for other chemicals, it seems that it could be a common problem that has not yet (but needs to be) recognized by researchers who are using dyes as surrogates for water and chemical movement.

REFERENCES

Andreini, M.S. and T.S. Steenhuis. 1990. Preferential paths of flow under conventional and conservation tillage. Geoderma, 46:85-102.

Bouma, J., A. Jongerius, O. Boersma, A. Jager, and D. Schoonderbeek. 1977. The function of different types of macropores during saturated flow through four swelling soil horizons. Soil Sci. Soc. Am. J. 41:945-950.

Bowman, R.S. 1984. Evaluation of some new tracers for soil water studies. Soil Sci. Soc. Am. J. 48:987-993.

Brusseau, M.L. and P.S.C. Rao. 1989. Sorption nonideality during organic contaminant transport in porous media. Crit. Rev. Environ. Control. 19:33-99.

Cameron, D.R. and A. Klute. 1977. Convective-dispersive solute transport with a combined equilibrium and kinetic adsorption model. Wat. Resou. Res. 13:183-188.

Coats, K.H. and B.D. Smith. 1964. Dead-end pore volume and dispersion in porous media. Soc. Pet. Eng. J. 4:73-84.

Davidson, J.M., C.E. Rieck, and P.W. Santelmann. 1968. Influence of water flux and porous material on the movement of selected herbicides. Soil Sci. Soc. Am. Proc. 32:629-633.

Flury, M., H. Flühler, W.A. Jury, and J. Leuenberger. 1994. Susceptibility of soils to preferential flow of water: A field study. Wat. Resou. Res. 30:1945-1954.

Flury, M. and H. Flühler. 1994. Brilliant Blue FCF as a dye tracer for solute transport studies - A toxicological overview. J. Environ. Qual. 23:1108-1112.

Flury, M. and H. Flühler. 1995. Tracer characteristics of brilliant blue FCF. Soil Sci. Soc. Am. J. 59:22-27.

Kung, K. -J.S. 1990. 1990. Preferential flow in a sandy vadose zone: 1. Field observation. Geoderma 46:51-58.

Mallawatantri, A. 1994. Processes and factors influencing fate and movement of agrochemicals in rainfed and irrigated management. Ph.D. Dissertation, Washington State University, Pullman, Washington.

McCall, P.J. D.A. Laskowski, R.L. Swan, and H.J. Dishburger. 1980. Measurement of sorption coefficients of organic chemicals and their use in environmental fate analysis. *In:* Zweig, G., ed. Test protocols for environmental fate and movement of toxicants. Proc. Symp. 94th Ann. Mtgs. Oct. 1980. Assoc. Offic. Anal. Chem. Arlington, VA..

Nkedi-Kizza, P., J.W. Biggar, H.M. Selim, M. Th. van Genuchten, P.J. Wierenga, J.M. Davidson, and D.R. Nielsen. 1984. On the equivalence of two conceptual models for describing ion exchange during transport through an aggregated Oxisol. Wat. Resour. Res. 20:1123-1130.

Omoti, U. and A. Wild. 1979. Use of fluorescent dyes to mark the pathways of solute movement through soils under leaching conditions: 1. Laboratory experiments. Soil Sci. 128:28-33.

Parker, J.C. and M. Th. van Genuchten. 1984. Determining transport parameters from laboratory and field tracer experiments. Bulletin 84-3. Virginia Agric. Exper. Sta., Blacksburg, VA. 96pp.

Pang, Xueping. 1995. Field and computer modeling studies on soil hydrology in the central sands of Minnesota: Percolation probabilities, risk assessment of nitrate leaching, and percolation losses form drip *vs.* sprinkler irritation. PhD dissertation, University of Minnesota, St. Paul.

Rao, P.S.C., J.M. Davidson, R.E. Jessup, and H.M. Selim. 1979. Evaluation of conceptual models for describing non-equilibrium adsorption-desorption of pesticides during steady-flow in soils. Soil Sci. Soc. Am. J. 43:22-28.

Roy, W.R., I.G. Krapac, S.F.J. Chou, and R.A. Griffin. 1987. Batch-type adsorption procedures for estimating soil attenuation of chemicals. Draft Technical Resource Document for Public Comment. Illinois State Geological Survey Div., Champaign. Prepared for Environmental Protection Agency, Washington, DC.

Selim, H.M., R.S. Mansell, and L.W. Zelazny. 1976. Modeling reactions and transport of potassium in soils. Soil Sci. 122:77-84.

Skopp, J. and A.W. Warrick. 1974. A two-phase model for the miscible displacement of reactive solutes in soils. Soil Sci. Soc. Am. J. 38:545-550.

Skopp, J. 1986. Analysis of time-dependent chemical processes in soils. J. Environ. Qual. 15:205-213.

Smart, P.L. and I.M.S. Laidlaw. 1977. An evaluation of some fluorescent dyes for water tracing. Water Resour. Res. 13:15-33.

Trudgill, S.T. 1987. Soil water dye tracing, with special reference to the use of Rhodamine Wt, Lissamine FF and Amino G acid. Hydrol. Process. 1:149-170.

van Genuchten, M. Th., J. M. Davidson, and P. J. Wierenga. 1974. An evaluation of kinetic and equilibrium equations for the prediction of pesticide movement though porous media.

Table 3-1. Properties of the Verndale sandy loam. Unless otherwise noted, all values were measured by Sexton (1992) in an area approximately 200 yards from our experimental site.

Horizon	Depth	Sand	Silt	Clay	Organic Carbon	Bulk Density	1:1 $CaCl_2$ pH	$\theta_{0.1MPa}$	$\theta_{1.5MPa}$	K_{sat}
	cm	------ $g\ kg^{-1}$ ------		$g\ kg^{-1}$	$Mg\ m^{-3}$			-- $cm^3\ cm^{-3}$ --		$mm\ hr^{-1}$
Ap	0 - 26	79	13	8	1.3	1.57	5.28	0.23	0.07	47.4
Bt	27 - 40	71	19	10	0.7	1.79	5.38	0.26	0.10	13.8
2BC	41 - 52	80	13	7	-	-	-	-	-	49.8
2C	53 - 100	92	5	3	-	-	5.74	0.13†	<0.04‡	120†

† From X. Pang (1995)
‡ Water content measured at 1.2 MPa by X. Pang (1995) was 0.04 $cm^3\ cm^{-3}$.

Table 3-2. Environmental conditions (temperature and solution pH) present during adsorption isotherm experiments, dye concentration measured in dye-blanks, and equivalent dye concentrations measured in soil-blanks for the shaking times evaluated.

	Shaking Time (h) 1	3	24	48	72
Temperature					
°C (± std)	23.0(0.5)	24.1(0.4)	23.3(0.6)	24.3(0.4)	23.9(0.4)
pH					
Dye Blank (no soil)	5.96	6.02	5.95	6.00	6.26
Soil Blanks (no dye)					
Ap	5.79	5.79	5.89	5.68	6.23
Bt	5.80	5.86	5.93	5.90	6.27
C	5.88	5.92	6.11	6.10	6.30
Dye Concentration† ($mg\ l^{-1}$)					
Dye Blank (no soil)	4.89	4.91	4.85	4.94	4.82
Soil Blanks (no dye)					
Ap	0.036	0.036	0.020	0.012	0.043
Bt	0.020	0.033	0.003	0.000	0.016
C	0.026	0.030	0.000	0.000	0.009

† Initial concentration for 'Dye Blanks' was 5 mg l^{-1}. 'Soil Blanks' contained only 0.005*M* $CaCl_2$ and no dye. Concentrations shown here for the 'Soil Blanks' are background absorbance converted to concentration basis. In all cases, background soil absorbance represented less than 5 % of the lowest solution concentration used in the experiment.

Table 3-3. Relationship of soil:solution ratio to the fraction of dye removed from solution, and the corresponding solution (C_s) and adsorbed (C_a) dye concentrations for the three soil horizons after 24 h shaking. Each value is the mean of duplicate samples. Unless otherwise noted, the coefficient of variation, CV, (CV = 100*(standard deviation)/mean) between the duplicates was less than 5 percent.

Soil Horizon	Soil:Solution Ratio	C_s	C_a	Fraction Removed
	(unitless)	mg l^{-1}	mg kg^{-1}	(unitless)
Ap	1:4	4.65	21.5	0.534
	1:10	6.92	31.0	0.308
	1:20	8.14	37.4	0.185
	1:100	9.73	55.4	0.027†
	1:500	9.88	58.6	0.011†††
Bt	1:4	1.20	35.2	0.880
	1:10	2.78	72.1	0.722
	1:20	4.36	112.6	0.564
	1:100	8.59	281.8	0.141
	1:500	9.35	324.9	0.065††
C	1:4	5.21	19.2	0.479
	1:10	7.16	28.4	0.284
	1:20	7.99	40.0	0.201
	1:100	9.63	73.0	0.037†
	1:500	9.83	85.7	0.017†††

† CC = 5-10% †† CV = 10-20% ††† CV = 25-30%

Table 3-4. Results of equilibration adsorption measurements determined for our soil using the procedure reported by Flury and Fühler (1995). Adsorbed concentration (C_a) and fraction removed were calculated from solution concentration (C_{si}) as described in the text. the procedure they reported was 3 h shaking, a 1:1.5 shaking time, 0.01*M* $CaCl_2$ background electrolyte, and the initial solution concentrations (C_{si}) given below. The coefficient of variation (CV)† between the duplicates was less than 5% for all samples.

Soil Horizon	C_{si}	C_s	C_a	Fraction Removed
	mg l^{-1}	mg l^{-1}	mg kg^{-1}	(unitless)
Ap	1	0.28	1.09	0.72
	2	0.51	2.25	0.75
	3	0.71	3.46	0.76
	5	1.22	5.70	0.76
Bt	1	0.04	1.44	0.96
	2	0.05	2.92	0.98
	3	0.05	4.41	0.98
	5	0.11	7.33	0.98
C	1	0.19	1.21	0.81
	2	0.50	2.24	0.75
	3	0.84	3.23	0.72
	5	1.42	5.35	0.72

Table 3-5. Relationship of shaking time to adsorbed (C_a) and solution (C_s) concentrations at several initial solution concentrations (C_i).

	Shaking	Ap			Bt			C		
C_i†	Time	C_s‡	C_a§	ΔC_s¶	C_s	C_a	ΔC_s	C_s	C_a	ΔC_s
mg l^{-1}	h	mg l^{-1}	mg kg^{-1}	%	mg l^{-1}	mg kg^{-1}	%	mg l^{-1}	mg kg^{-1}	%
1	1	0.79	2.10	-	0.20	8.06	-	0.84	1.56	-
	3	0.74	2.58	5.9	0.17	8.31	12.8	0.81	1.88	3.8
	24	0.62	3.82	16.6	0.10	8.96	38.8	0.70	3.04	14.2
	48	0.58	4.20	5.8	0.06	9.38	41.2	0.65	3.53	7.0
	72	0.54	4.66	8.0	0.10	9.03	-57.8	0.62	3.81	4.4
3	1	2.35	6.55	-	0.92	20.82	-	2.50	4.97	-
	3	2.31	6.95	1.7	0.83	21.64	9.0	2.51	4.91	-0.2
	24	1.96	10.49	15.2	0.60	23.96	27.8	2.27	7.28	9.4
	48	1.98	10.22	-1.4	0.59	24.08	2.1	2.23	7.72	1.9
	72	1.71	12.61	12.3	0.54	24.56	8.2	2.14	8.67	4.3
5	1	3.86	11.44	-	1.67	33.24	-	4.00	10.05	-
	3	3.79	12.19	1.9	1.50	34.94	10.2	4.00	10.02	-0.1
	24	3.26	17.52	14.0	1.28	37.11	14.5	3.60	13.98	9.9
	48	3.22	17.93	1.2	1.14	38.54	11.2	3.70	12.98	-2.8
	72	2.93	20.85	9.0	1.07	39.24	6.1	3.49	15.13	5.8
10	1	7.94	20.76	-	3.51	64.78	-	7.86	21.42	-
	3	7.68	23.37	3.3	3.36	66.64	4.5	7.68	23.30	2.4
	24	6.87	31.52	10.5	2.89	71.03	14.0	7.21	27.97	6.1
	48	6.56	34.60	4.4	2.74	72.43	4.9	7.02	29.86	2.6
	72	6.18	38.53	5.9	2.51	74.78	8.6	6.98	30.31	0.6
20	1	15.82	42.16	-	6.78	132.00	-	15.12	48.91	-
	3	15.40	46.33	2.6	6.83	131.49	-0.8	15.05	49.60	0.4
	24	13.84	62.00	10.1	5.62	143.53	17.7	13.78	62.32	8.4
	48	13.55	64.97	2.1	5.38	145.91	4.2	14.25	57.61	-3.4
	72	12.65	74.03	6.6	5.04	149.31	6.3	13.30	67.13	6.7

† C_i = Initial solution concentration. ‡C_s = Solution concentration measured after shaking. § C_a = Adsorbed concentration calculated from C_s. ¶ ΔC_s = Change in solution concentration: ΔC_s (%) = $100(C_{t-24h} - C_t)/C_{t-24}$ where C_t is the concentration at time t, and C_{t-24} is the concentration 24 h earlier.

Table 3-6. Best fit values of the coefficients of the linearized Freundlich (Kd), non-linear Freundlich (Kf and 1/n), and Langmuir (K_L) isotherm models and corresponding correlation coefficients (r^2) for three horizons at various shaking times. NS indicates model was not significant at $p < 0.05$.

Horizon	Shaking Time	Kd	r^2	1/n	Kf	r^2	M	K_L	r^2
	h	L kg^{-1}			L kg^{-1}				
Ap	1	2.67	0.999	0.9966	2.74	0.998	-	-	NS
	3	3.02	0.997	0.9666	3.23	0.990	-	-	NS
	24	4.54	0.997	0.8918	5.86	0.998	233.7	0.0248	0.757
	48	4.92	0.996	0.8853	6.30	0.990	275.4	0.0221	0.442
	72	6.00	0.996	0.8739	7.98	0.999	245.0	0.0326	0.790
Bt	1	19.36	0.997	0.7844	24.94	0.983	329.8	0.0826	0.446
	3	19.86	0.991	0.6801	27.93	0.939	221.3	0.1509	0.533
	24	25.59	0.994	0.6732	36.94	0.978	244.2	0.1896	0.566
	48	27.31	0.993	0.5620	42.07	0.930	223.0	0.2467	0.562
	72	30.03	0.994	0.6950	41.62	0.987	261.8	0.2080	0.626
C	1	3.06	0.988	1.2080	1.79	0.996	-62.0	-0.0306	0.767
	3	3.16	0.992	1.1670	2.00	0.984	-71.5	-0.0286	0.588
	24	4.32	0.995	1.0180	3.84	0.987	-	-	NS
	48	4.04	0.985	0.9260	4.48	0.977	-	-	NS
	72	4.85	0.981	0.9341	5.12	0.975	-	-	NS
Flury and Flühler (1995) Procedure†									
Ap	3	4.65	0.998	1.1183	4.74	0.986	-	-	NS
Bt	3	64.83	0.933	0.8620	40.92	0.528	-	-	NS
C	3	3.92	0.990	0.7124	3.79	0.988	10.8	0.5691	0.750

† These are the values determined using our soil and the procedure reported by Flury and Flühler (1995). See text for details of the procedure.

Table 3-7. Organic carbon (f_{oc}), clay content (f_{clay}), and linear distribution coefficient (Kd), and Kd values normalized for organic carbon (K_{oc}) and clay content (K_{clay}).

			Equilibration time (h)					
			1			24		
Horizon	f_{oc}	f_{clay}	Kd	K_{oc}	K_{clay}	Kd	K_{oc}	K_{clay}
	--- g g^{-1} ---		-------- L kg^{-1} --------			-------- L kg^{-1} --------		
Ap	0.013	0.08	2.67	205	33	4.54	349	57
Bt	0.007	0.10	19.4	2766	194	25.59	3658	256
C	0.001	0.03	30.6	1224	102	4.32	1782	1140

Table 3-8. Summary of retardation coefficient (*R'*) values calculated using the advance of wetting and dye fronts for two rates of application in three soil horizons.

	R'	
	FLOOD	INTERMITTENT
Ap	1 to 1.2	2 to 3
Bt	2 to 13	5 to 12
C	1.1 to 1.4	3 to 6

Table 3-9. Dye retardation (*R'*) in the Ap horizon as a function of time, calculated from the distance traveled by the wetting front (L_{H2O}) and dye front (L_{dye}). Each replicate was run in a separate column.

	Rep 1			Rep 2			Rep 3		
Time†	L_{water}	L_{dye}	R'	L_{water}	L_{dye}	R'	L_{water}	L_{dye}	R'
min	--- cm ---			--- cm ---			--- cm ---		
INTERMITTENT									
10	4.8	2.0	2.4	5.0	2.7	1.9	4.8	2.6	1.8
70	7.8	4.5	1.7	7.8	4.3	1.8	7.0	4.0	1.8
130	10.2	5.5	1.9	11.0	5.0	2.2	10.7	5.0	2.1
191	14.7	5.5	2.7	15.1	6.5	2.3	14.9	6.5	2.3
252	19.5	6.0	3.3	19.2	7.9	2.4	18.6	8.3	2.2
313	23.2	7.6	3.1	23.9	9.2	2.6	22.5	8.7	2.6
374	27.8	9.0	3.1	28.0	10.5	2.7	28.0	10.5	2.7
435	30.8	11.3	2.7	31.1	12.0	2.6	31.1	12.0	2.6
FLOOD									
2	6.0	5.0	1.2	6.9	6.5	1.1	4.8	4.0	1.2
3	7.5	6.5	1.2	9.2	8.9	1.0	5.8	5.0	1.2
5	10.5	8.5	1.2	12.0	11.6	1.0	8.3	7.2	1.2
8	15.5	10.5	1.5	16.5	15.7	1.1	11.6	10.0	1.2

† Time given corresponds to elapsed time since first addition of dye. for INTERMITTENT the given times correspond to 10 min after each addition of a dye solution aliquot. For FLOOD< the time given is elapsed time since the start of ponding.

Table 3-10 Dye retardation (*R'*) in the Bt and C horizons as a function of time, calculated from the distance traveled by the wetting front (L_{H2O}) and dye front (L_{dye}). Each replicate was run in a separate column.

	Rep 1					Rep 2			
	Time	L_{water}	L_{dye}	R'		Time	L_{water}	L_{dye}	R'
	min	cm	cm			min	cm	cm	
				Bt Horizon					
INTERMITTENT									
	10	3.6	0.5	7.2		10	4.1	0.7	5.9
	70	6.8	1.0	6.8		70	7.0	1.6	4.4
	130	9.2	1.3	7.0		130	10.0	1.8	5.6
	188	12.5	1.4	8.9		188	13.0	1.9	6.8
	250	15.6	1.9	8.2		250	16.0	2.0	8.0
	310	19.5	2.1	9.3		310	19.5	2.0	9.8
	370	22.7	2.4	9.4		370	23.2	2.1	11.0
	430	25.5	2.5	10.2		430	26.0	2.1	12.4
	490	28.7	2.8	10.2					
	550	31.5	2.9	10.8					
FLOOD 4	4.0	1.2	3.3		2	3.1	1.6	1.9	
	5	4.5	1.2	3.8		4	4.9	1.8	2.7
	10	6.4	1.3	4.9		6	6.3	2.0	3.2
	20	9.0	1.5	6.0		10	8.6	2.6	3.3
	30	10.8	1.5	7.2		15	11.2	2.8	4.0
	40	12.6	1.5	8.4		20	13.6	3.0	4.5
	61	15.5	1.5	10.3		30	16.8	3.4	4.9
	116	21.6	1.8	12.0		40	22.0	3.6	6.1
	177	27.7	2.0	13.8		50	22.5	3.8	5.9
	239	32.5	2.4	13.5		60	25.1	3.8	6.6
						70	28.0	4.2	6.7
						90	31.5	4.5	7.0
						120	37.4	5.2	7.2

(continued next page)

Table 3-10 (continued).

	Rep 1					Rep 2			
	Time	L_{water}	L_{dye}	R'		Time	L_{water}	L_{dye}	R'
	min	cm	cm			min	cm	cm	
				C Horizon					
INTERMITTENT									
	10	5.6	2.5	2.2		10	5.2	0	-
	70	11.8	3.7	3.2		70	11.7	3.5	3.3
	130	16.5	4.0	4.1		130	17.3	4.0	4.3
	190	24.6	5.5	4.5		190	24.6	5.0	4.9
	320	32.0	6.5	4.9		250	32.8	6.5	5.0
						310	40.0	6.5	6.2
FLOOD 0.5	11.0	9.7	1.1		0.5	13.2	11.0	1.2	
	1.0	18.3	15.1	1.2		1.0	20.0	15.5	1.3
	1.5	24.0	18.8	1.3		1.5	25.0	18.5	1.4
	2.0	28.6	20.5	1.4		2.0	30.0	21.0	1.4

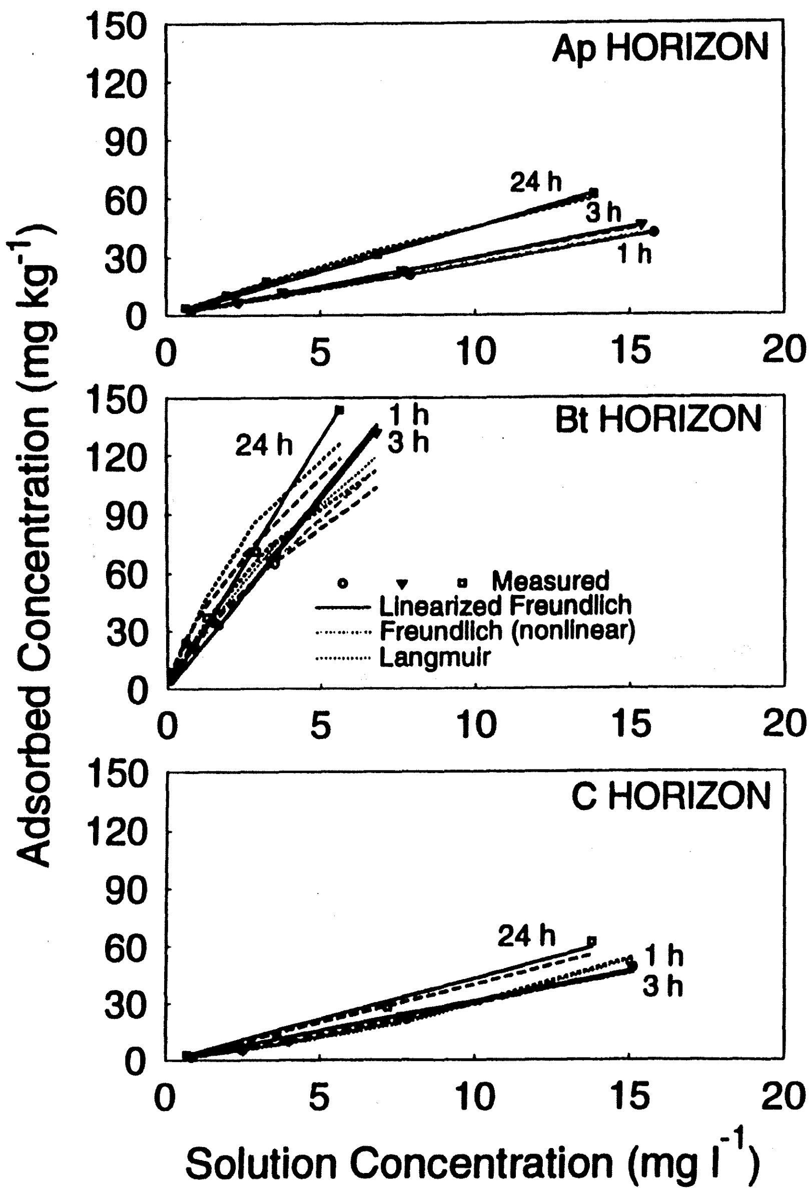

Figure 3-1. Measured adsorption isotherms with Freundlich, linearized Freundlich, and Langmuir fitted models for shaking times of 1, 3, and 24 h in three horizons of Verndale sandy loam.

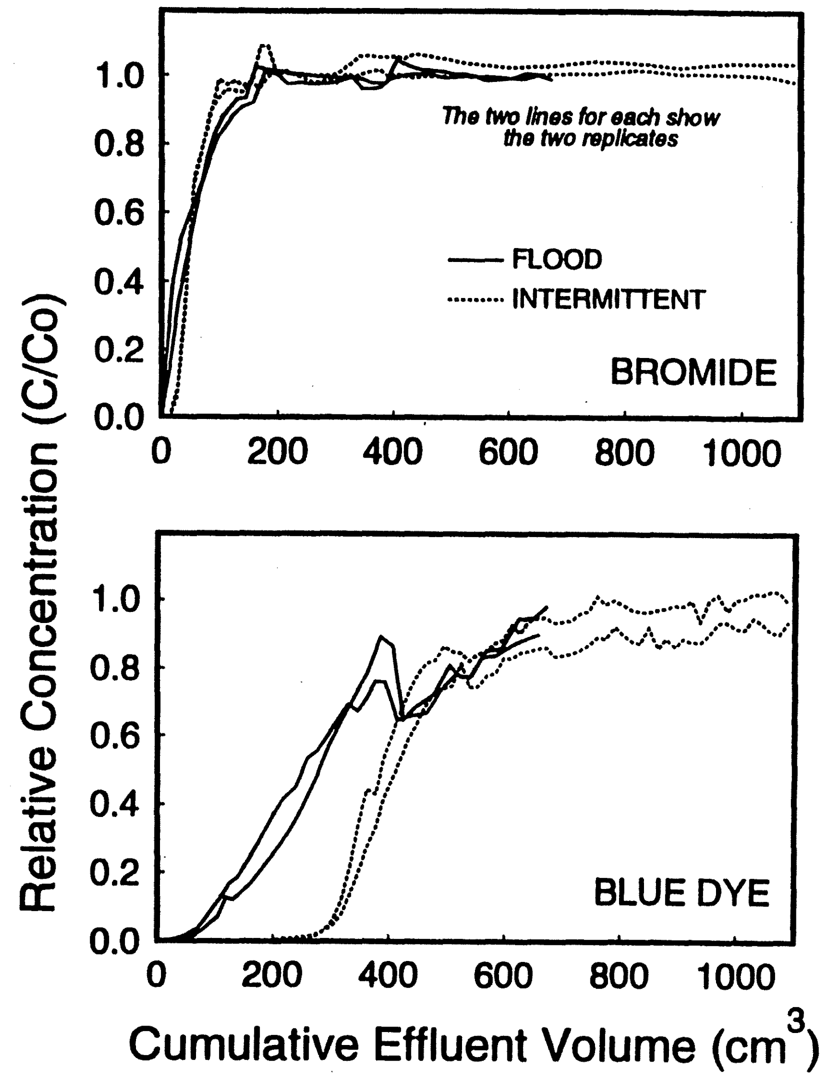

Figure 3-2. Breakthrough curves for the dye FD&C Blue #1 and bromide under FLOOD and INTERMITTENT conditions for the Ap horizon.

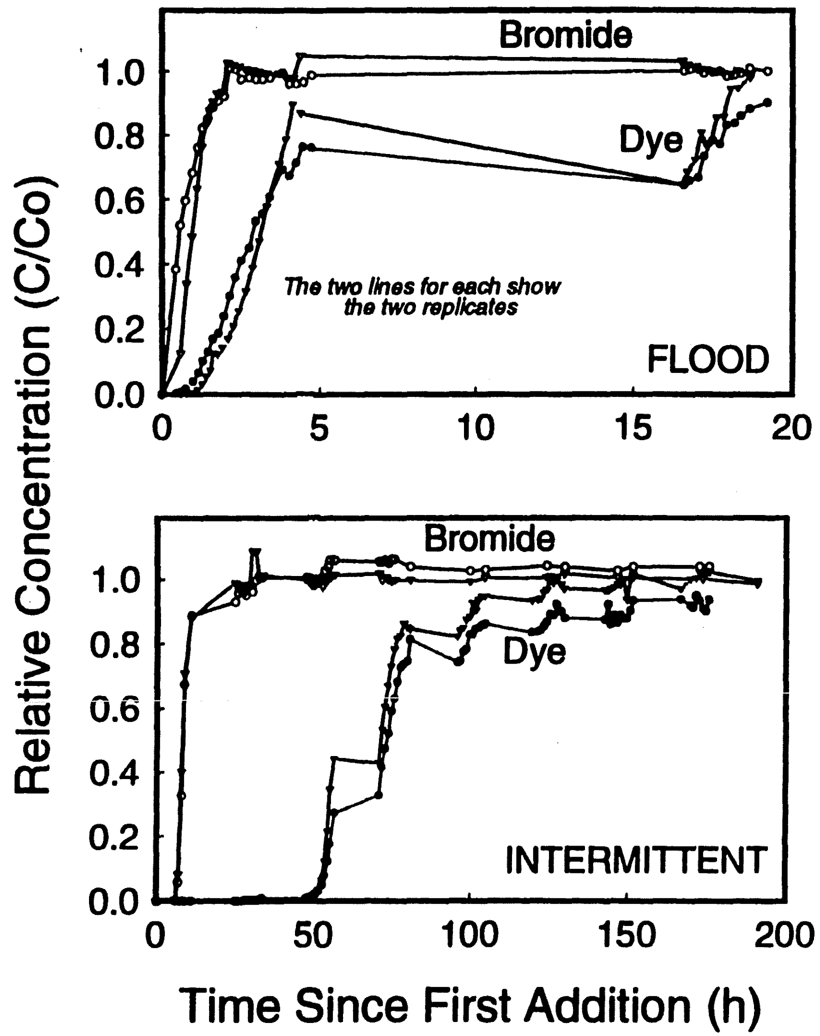

Figure 3-3. Effluent concentration curves for FD&C Blue #1 dye and bromide as a function of time for FLOOD and INTERMITTENT conditions for the Ap horizon.

FIELD AND COMPUTER MODELING STUDIES ON SOIL HYDROLOGY IN THE CENTRAL SANDS OF MINNESOTA: PERCOLATION PROBABILITIES, RISK ASSESSMENT OF NITRATE LEACHING, AND PERCOLATION LOSSES FROM DRIP VS. SPRINKLER IRRIGATION

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

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FOR THE DEGREE OF
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ABSTRACT

A series of experimental and modeling studies on the hydrology of sandy outwash soils in the Central Minnesota are described in this thesis. The first study deals with probabilities of rain, and the amount of excess water that might be available for leaching in soils of various water holding capacities. Simulation results over 41 years showed that for a median year, annual percolation losses could be as high as 25 cm for a soil with 5 cm water holding capacity. The second study deals with the use of CERES-Maize model to identify management practices that can minimize nitrate leaching in the Central Sands of Minnesota. Simulation results with 31 years of climatic data showed that (1) irrigation trigger of 30-40% and fertilizer application of about 180 kg ha^{-1} are sufficient to achieve maximum corn yield in this region, and (2) N leaching in these soils is mainly caused by excess irrigation or unexpected rains that occur right after an irrigation.

In the third and fourth studies, we evaluated the potential of subsurface drip irrigation as an alternative in providing substantial unfilled soil pore space to hold water from the unforeseen rains that may occur right after an irrigation. Field measurements of wetting and drying patterns showed that change in water content were large both under the furrow and just below the center of the ridge. The changes under the furrow were due to a greater amount of infiltration as results of water runoff from the ridge whereas the change just below the ridge were due to more water arriving at the base of the plant from stem flow. Simulation with SWMS_2D model showed that 40 cm was the optimum depth of drip placement for Verndale sandy loam because of the presence of Bt horizon. Deeper placement of drip led to excess percolation due to higher hydraulic conductivity of C horizon whereas shallow placement potentially present problems of drip tape being ripped during potato harvest. It is concluded that buried drip compared to sprinkler irrigation could potentially reduce water percolation losses especially if rain came right after irrigation.

Chapter 1. SYNOPSIS

This thesis quantifies the role of major factors such as climate, soils, and fertilizer and irrigation management on water percolation and nitrate leaching through outwash soils in Central Sands of Minnesota. In Chapter 2 we present the probability of rain, and the amount of excess water that might be available for leaching in soils of various water holding capacities. In Chapter 3, we outline various irrigation and fertilizer management scenarios that can minimize nitrate leaching without significantly reducing crop yield. In Chapter 4 we discuss the results of a field experiment on soil water dynamics under growing potato plants in sprinkler and drip irrigated soils. In this chapter, we also evaluate whether or not subsurface drip irrigation might be a possible alternative in providing substantial unfilled pore space to hold water from unforeseen rains that might occur right after irrigation. Finally in Chapter 5, we discuss the capability of a mechanistic two dimensional model (SWMS_2D) in quantifying the impact of stem flow and ridge-furrow configuration on the soil wetting and drying patterns, and the degree of percolation for both sprinkler and subsurface drip irrigated lands.

Nation wide, there is an increased concern regarding the degradation of groundwater quality from land applied chemicals. This concern is justified considering that several studies have documented the presence of nitrate and pesticides in groundwater (Hallberg et al. 1984; Nielsen and Lee, 1987). In Minnesota, the survey by Klaseus et al. (1988) found elevated nitrate and pesticides in 43 and 33%, respectively, of the 500 wells tested in 51 counties. A significant number of these contaminated wells were in glacial outwash soils of Central Minnesota. A USGS study (Myette, 1984) of 124 wells in Hubbard, Morrison, Otter Tail and Wadena counties of Central Minnesota showed that nitrate concentration has been continuously increasing since the 1960's. In some wells, concentration of nitrate has exceeded the EPA drinking water standards of 10 mg l^{-1}.

Typically, soils in the Central Sands of Minnesota are developed from glacial outwash parent material. These soils have low production potential because of low soil fertility and lower capacity to hold water. The precipitation alone can not sustain most agricultural crops during the growing season. Since ground water is shallow and easily accessible, extensive areas have been brought under cultivation since the 1960's by supplementing crop water needs with irrigation. Major crops of the area are corn and potato. These crops are often excessively fertilized to insure maximum yield and higher quality.

Shallow surficial aquifers in the Central Sands of Minnesota are also the source of drinking water supply for most of the communities in the area. Contamination of the groundwater is primarily because the soils are non-adsorbing and have low water holding capacities. In the past four years, several studies have been underway at the University of Minnesota to quantify the potential of nitrate leaching and to identify fertilizer and irrigation management practices that could minimize this leaching from the soils developed in glacial outwash in the Central Sands of Minnesota. The results reported in this thesis are part of those studies.

In **Chapter 2**, we used a hydrologic water balance computer model to identify the peak leaching periods and the corresponding amount of percolation based on long-term daily meteorological data, and to compute the annual excess precipitation and irrigation that may percolate through Minnesota outwash soils with various water holding capacities. The procedure involved daily calculation of percolation based on soil water holding capacity, rainfall amount and the evapotranspiration. Evapotranspiration was estimated using the Blaney-Criddle Method, which employs air temperature, day length and a crop factor as its inputs. Simulation results over 41 years (1950-1990) showed that at 50 percent probability (median year) annual percolation losses could be as high as 28 cm for a soil with 2.5 cm water holding capacity. As expected, the percolation losses decrease with an increase in soil water holding capacity. The occurrence of percolation losses in this region is highest during spring and fall because of limited loss of water loss evapotranspiration.

Since soils and climatic factors can not be easily manipulated, the only option available to minimize nitrate leaching from these soils is through the management of irrigation and fertilizer. However to sustain the agriculture of the area, irrigation and fertilizer management scenarios must be such that they minimize nitrate leaching without significantly reducing crop yield. In the past, recommendations for best management of fertilizer and irrigation have largely been based on crop yield data and very little attention has been paid to the potential of nitrate leaching under the recommended best management practices. The true best management practices should not only consider the crop yield but also the extent of nitrate leaching covering several weather cycles. This type of information is lacking for outwash soils in the Central Sands of Minnesota because the cost of setting up long-term experiments and gathering data is prohibitive. One of the inexpensive means of obtaining this data is through simulation models that integrate soil, climate and management information to predict crop growth, and availability and movement of nitrogen in the root zone. One such model is the Crop-Environment-Resource-Synthesis (CERES) -Maize model (Jones and Kiniry, 1986).

The focus of the study covered in **Chapter 3** was to test and validate the CERES-Maize model under the soil and climatic conditions of the Central Sands of Minnesota, and then identify the management practices that can minimize nitrate leaching. An additional objective of the study was to develop a procedure that could characterize the risk potential of soils to nitrate leaching under various management scenarios over several weather cycles. The validation was done against the experimental data on corn yield, N uptake and N leaching for four fertilizer application rates and two irrigation schedules on Verndale sandy loam (coarse loamy over sandy, mixed, frigid, Udic Argiboroll) during 1991 and 1992 at Staples, MN (Sexton, 1993). In general, simulated values were close to the observed data. Simulation with 31 years of climatic data showed that N leaching in these soils was mainly caused by excess irrigation or unexpected rains that may occur right after irrigation. Therefore we conclude that in order to minimize N leaching, irrigation should be applied so that there was always some unfilled porespace in soil to capture the unforeseen rain that may occur after irrigation.

The simulation results showed that for outwash soils of Minnesota, selecting N application rates based on yield goal is not appropriate because climate is a major determinant of the yield in the area. The results also showed that irrigation trigger of about 30-40% and fertilizer application of about 180 $kg\,ha^{-1}$ are sufficient for achieving maximum corn yield. A procedure that characterizes the risk potential of these soils to N leaching based on the output results of long-term simulation of CERES-Maize is also presented. The procedure identifies fertilizer and irrigation management practices best suited for maximum yield and minimum N leaching for a given soil and climatic condition.

There are several ways to maintain unfilled soil pore space and thus minimize the impact of unforeseen rains on nutrient leaching. These include: 1) High deficit irrigation so that the period between irrigation is large and thus there is a greater chance of capturing water from unforeseen rains, 2) Irrigating soils to water contents less than field capacity and thus there is some unfilled pore space that can capture water from unforeseen rains, and 3) Localizing irrigation to plant roots and leaving the soil between the plants unfilled to capture unforeseen rains. For soils irrigated with sprinkler irrigation systems, the first two options are appropriate. However, the third option can only be achieved with a drip irrigation system. A study to evaluate the effectiveness of these and other management options to minimize nitrate leaching from soils in the Central Sands of Minnesota has been underway since 1994 (Waddell, 1994). **In Chapter 4**, we report on the evaluation whether or not subsurface drip irrigation can be a possible alternative in providing substantial unfilled pore space to hold water from unforeseen rains that might occur right after irrigation.

The depth and placement of a drip line relative to the potato hill is important in order to maximize the availability of water to plant and reduce nitrate leaching from irrigation. Soil drying (water uptake by potato plant) and wetting (rain or drip) patterns both for sprinkler and drip irrigation can be helpful in understanding water movement under a growing potato plant in a ridge-furrow system. Since drip irrigation is relatively new and has not been extensively used in potato production, there is little information in the literature on the water uptake patterns by a potato plant in drip irrigated soils (Shalhevet et al., 1983). In addition, there is not much information on the comparison of soil wetting patterns between subsurface drip and sprinkler irrigation system under a ridge-furrow configuration, although it has been postulated (Saffigna et al., 1976) that the flux of water entering the soil surface from either rain or sprinkler irrigation varies with the position along the ridge. Saffinga et al. (1976) also showed that there was some preferential transport of rain or sprinkler applied water along the stem to the base of the potato plant.

Estimates of potato water use are essential in developing irrigation scheduling schemes to meet plant water needs. One of the important factor in estimating crop water use is the crop coefficient. Most of the experimental studies for estimating crop coefficients for potatoes have been under arid climate. To the author's knowledge, there is no information on daily water use for potatoes in Minnesota. In **Chapter 4** we also report on the crop water use coefficient for potato plant for climate of the upper Mid-West.

The field experiment reported in **Chapter 4** consisted of measuring hourly soil water content profiles with Time Domain Reflectometry (TDR) probes under growing potato plants in both sprinkler and drip irrigated plots in Verndale sandy loam at Staples, MN. Drip lines were installed at a depth of 25 cm below the soil surface. For each irrigation treatment, 16 TDR probes were installed at 15 cm intervals both in the vertical and the horizontal directions. Since greater changes in soil water content were expected near the soil surface, more probes were installed near the surface than at deeper depths.

Wetting and drying patterns showed that there was little water movement to the upper parts of the ridge in the drip irrigated plot. Under both furrow and just below the center of the ridge, there was a large change in water content. This large change in soil water content under the furrow was due to a greater amount of infiltration as a result of water runoff from the ridge. Large changes in soil water content just below the ridge was due to more water arriving at the base of the plant from stem flow and then some preferential movement through cracks created by the expanding tubers. Small changes in water contents just below the shoulder of the ridge compared to just below the furrow were due to higher runoff from the shoulder of the ridge and thus less water infiltration.

There was no significant difference in evapotranspiration (ET) between the drip and sprinkler irrigated plots since soil water was not limiting for both the treatments. Seasonal ET for both irrigation treatments averaged 265 mm. This was equivalent to daily average ET of 2.9 mm d^{-1} for both drip and sprinkler treatments. Seasonal drainage (DR) was 136 and 67 mm for the drip and the sprinkler irrigated plots, respectively. This is equivalent to an average daily drainage rate was 1.5 and 0.8 mm d^{-1} for the drip and the sprinkler irrigated plots, respectively. The higher seasonal DR from the drip irrigated plot was due to over application for the drip irrigated plot. In the calculation, it was assumed that water application in the drip plot was over the total plot area rather than the much smaller area just around the drip line. Crop coefficient (Kc) for potatoes was about 1 from middle of June to middle of August for both sprinkler and drip irrigated plots. This observation is very similar to observations reported in the literature that Kc is equal to 1.0 after the crop canopy is fully developed.

Experimental results suggested that water movement in the soil profile under a ridge-furrow system is a two dimension problem. Since the experimental characterization of water movement in the soil profile under a ridge-furrow system for a whole range of treatments is expensive and time consuming, in **Chapter 5** we discuss the use of a mechanistic 2-dimensional model (SWMS_2D) to evaluate the role of stem flow, and the depth of drip placement on percolation losses in subsurface drip irrigation treatments. Using the SWMS_2D model, we also quantify the differences in percolation between the sprinkler and drip irrigated plots.

Many studies have been done in the past on analytical and numerical solutions to the Richard's equation for two and three dimension water flow from a surface trickle source. However, there is little research reported on the two dimensional water flow from a subsurface drip irrigation. The finite element model SWMS_2D (ver. 1.2) has been developed in the U.S. Salinity Laboratory (Simunek et al., 1994). This model can simulate 2_D water movement in variably saturated media.

In this study, we choose the SWMS_2D model for its ability to handle the irregular soil surface configuration and water application through subsurface drip. After field testing of the model, we also ran some sensitivity analysis to identify the optimal placement of drip line with respect to the ridge, and to evaluate the role of plant canopy architecture and the ridge-furrow surface configuration on preferential flow patterns a growing potato plant.

Simulation results showed that there was not much water movement towards the upper part of the ridge when the drip was installed at 40 cm depth or deeper from the top of the ridge in Verndale sandy loam. This observation has important implications if drip irrigation is also used for application of fertilizer. Since the potato roots are not fully developed at the early stage of potato growth, the simulation results suggest that application of starter fertilizer will be better than the application of fertilizer through the drip line. Simulation results also showed that irrigation water applied through the buried drip could reduce the water percolation losses significantly compared to sprinkler irrigation method if a rain came right after the irrigation.

The major findings of this thesis are:

1. The best management practices should not only consider the crop yield but also the extent of nitrate leaching covering several weather cycles. Both yield and nitrate leaching data can be readily obtained through simulation models that integrate soil, climate, and irrigation and fertilizer management information to predict crop growth, and movement of nitrogen in the root zone. The simulation results showed that irrigation trigger of about 30-40% and fertilizer application of about 180 kg ha^{-1} are sufficient to achieve maximum corn yield in sandy soils developed in glacial outwash in the Central Sands of Minnesota. However in terms of N leaching to groundwater, the best N application rate is 100 kg N ha^{-1}. Both these rates are much smaller than the yield goal based recommended rate of 245 kg ha^{-1}. This suggests that selecting N application rates based on yield goal may not be appropriate because climatic parameters such as temperature and precipitation are the major determinants of crop yield in the Central Sands of Minnesota.

2. A procedure that characterizes the risk potential of sandy outwash soils to N leaching is developed based on the output results of long-term simulation of CERES--Maize. The procedure identifies fertilizer and irrigation management practices best suited for maximum yield and minimum N leaching for a given soil and climatic condition. With current emphasis on site specific farming, these risk indices linked with a soil survey data base could be a valuable tool in prescribing management practices that optimize yield and minimize nitrate leaching.

3. Both field and simulation results suggest that surface drip irrigation could be a possible alternative in providing substantial unfilled pore space to hold water from unforeseen rains that might occur right after irrigation, and thus help minimize water percolation and nitrate leaching in sandy soil developed in glacial outwash in the Central Sands of Minnesota.

REFERENCES

Hallberg, G. R., R. D. Libra, E. A. Bettis, and B. E. Hoyer. 1984. Hydrogeologic and water quality investigations in Big Spring Basin, Clayton County, Iowa: 1983 water year. Open-file Rep. No. 84-4. Iowa Geological Survey.

Jones, C. A. and Kiniry, J. R. (Ed.). 1986. the CERES-Maize: A simulation Model of Maize Growth and Development. Texas A & M University Press. College Station, Texas.

Klaseus, T. G., G. C. Buzicky, and E. C. Schneider. 1988. Pesticides and groundwater: Survey of selected Minnesota wells. Report for the Legislative Commission on Minnesota Resources, Minnesota Dept. of Health and Minnesota Dept. of Agriculture.

Myette, C. F. 1984. Groundwater quality appraisal of sand plain aquifers in Hubbard, Morrison, Otter tail, and Wadena counties, Minnesota. U.S. Geological survey. Water-Resources Investigations Report 84-4080. St. Paul, MN.

Nielsen, E. G. and L. K. Lee. 1987. The magnitude and costs of groundwater contamination from agriculture chemicals: A national perspective. Agricultural Economic Rep. No. 576, U.S. Dept. of Agriculture.

Saffigna, P. G., C. B. Tanner, and D. R. Keeney. 1976. Non-uniform infiltration under
potato canopies caused by interception, stemflow, and hilling. Agron. J. 68:337-342.

Sexton, B. T. 1993. Influence of nitrogen and irrigation management on corn and potato response and nitrogen leaching. M.S. thesis, Univ. of Minn., St. Paul, MN.

Shalhevet, J., D. Shimshi, and T. Meir. 1983. Potato irrigation requirements in a hot climate using sprinkler and drip irrigation. Agron. J. 75:13-16.

Simunek, J., T. Vogel and M. Th. van Genuchten. 1994. The SWMW_2D code for simulating water flow and solute transport in two-dimensional variably saturated media (Version 1.2). Research report No. 132. U.S. Salinity laboratory, ARS. U.S.D.A. Riverside, CA.

Waddell, J. 1994. Evaluation of drip and sprinkler irrigation and N management schemes on potato production and N leaching losses. A PhD project to be completed by 1997.

Chapter 2. PROBABILITIES OF PERCOLATION LOSSES IN MINNESOTA OUTWASH SOILS

ABSTRACT

Rapid drainage and low water holding capacities of soils in the glacial outwash region of Minnesota have been attributed as possible reasons for the contamination of groundwater from land applied chemicals. A study was undertaken to quantify the potential of various soils in this region to nitrate leaching and to identify the best fertilizer or irrigation management practices that will minimize this leaching. This simulation experiment is part of the study and was geared to identify the potential peak leaching period and the corresponding amount of percolation from soils in the Central Sands of Minnesota. The simulation procedure involved daily calculation of excess percolation based on soil water holding capacity, rainfall amount and evapotranspiration. Evapotranspiratipon was estimated using the Blaney-Criddle method, which employs air temperature, day length and a crop factor as its inputs. Simulation results over 41 years (1950-1990) showed that at 50 percent probability (median year) annual percolation losses could be as high as 25 cm for a soil with 2.5 cm water holding capacity. As expected, the percolation losses decrease with an increase in soil water holding capacity. Percolation losses in this region are highest during spring and fall because of limited water loss from soil by evapotranspiration.

INTRODUCTION

Nation wide, there is an increasing concern on the contamination of groundwater from land applied chemicals. This concern is justified considering that several studies have documented the presence of nitrate and pesticides in groundwater (Hallberg et al., 1984; Nielsen and Lee, 1987). A Minnesota survey (Klaseus et al., 1988) found pesticides and nitrate in 33% and 43%, respectively, of the 500 wells tested in 51 counties. Wells included in the survey covered both the shallow observation wells near the water table and the wells used for public and private drinking water supplies. In this survey, most of the contaminated wells were in the Southeast (Karst region) and Central (Sand Plain region) Minnesota.

Soils in Central Sands of Minnesota are typically developed from glacial outwash. These soils have low production potential because of low nitrogen content, rapid drainage, and low water holding capacities. The precipitation during the growing season can not sustain most agricultural crops on these soils. Since the ground water is shallow and easily accessible, extensive areas have been brought under cultivation since the 1960's by supplementing crop water needs with irrigation. Major crops of the area are corn and potato. Since potato is a high value crop, the nitrogen fertilizer applications are often excessive.

Shallow surficial aquifers in Central Minnesota are also the source of drinking water supply for most of the communities in the area. Contamination of the ground water is mostly because the soils are non-adsorbing and have low water holding capacities. Recently, a study was undertaken to quantify the potential of nitrate leaching from various soils of the outwash region of Minnesota and to identify fertilizer or irrigation management practices that will minimize this leaching. First step in this study was to understand the precipitation patterns of the area, the probability of leaching rain, and the amount of excess water that might be available for leaching. In this chapter we address some of these questions.

Blake et al. (1960) calculated the probabilities of drought and excess soil water in Minnesota based on a 25 year (1932-1956) record of precipitation. They used the Penman method to estimate evapotranspiration. These authors found that some Minnesota soils have excess moisture compared to the consumptive need of crops. At 50% probability (median year), the excess moisture ranges between 10 to 5 cm for soils with water holding capacities varying from 12.5 to 22.5 cm. In Central Minnesota, most of the excess moisture occurred during May and June which is also the time for crop planting and fertilizer application. This observation suggests that in Minnesota outwash soils a significant amount of nitrate leaching could occur during May and June.

In Blake et al. (1960) study there was no information on excess moisture from soils with low water holding capacities. The current study was undertaken to quantify maximum percolation losses from Minnesota outwash soils having various water holding capacities. The specific objectives of the study were to identify the peak leaching periods and the corresponding amount of percolation based on long-term daily meteorological data, and to compute the annual excess precipitation and irrigation that may percolate through Minnesota outwash soils with various water holding capacities.

PROCEDURES

The procedures involved calculating the daily water balance of a soil profile based on long-term daily precipitation, calculated daily evapotranspiration, and daily supplemental water from a given schedule of irrigation events.

$$P = R + I - ET - WHC + W_i \quad [1a]$$

$$\text{if } P \leq 0 \text{ then } P = 0 \quad [1b]$$

where P = amount of water that exceeds the water holding capacity and is defined as percolation in this study (cm), R = daily precipitation (cm), I = amount of irrigation for a given irrigation scenario (cm), ET = daily evapotranspiration (cm), WHC = water holding capacity (cm), and W_i = depth of water initially present in the soil (cm).

It was assumed that excess water (P) will percolate out of the root zone and can potentially carry nitrate to the ground water. For various irrigation scenarios, when R was less than WHC, an irrigation of a given amount (I) was applied and ET was set equal to zero.

In Equation [1], it is also assumed that there is no surface runoff. Since the landscape in the Central Sands of Minnesota is relatively flat and soils are coarse textured, the runoff from these soil will be negligible. Also, since the water balance calculations are on a daily basis, this study further assumes that rain and irrigation water is distributed fast enough in soil to bring it to its water holding capacity within a relatively short time (≤ 1 day). Considering that soils in Central Sands are highly porous, this assumption is realistic.

Evapotranspiration (ET) was calculated by multiplying the crop coefficient to calculated potential evaporation using the Blaney-Criddle method (Eq. [2]) (Seeley and Spoden, 1982).

$$ET=0.0254*(0.0173*(32+1.8*T)-0.314)*(32+1.8*T)*P*K \quad [2]$$

where T = daily mean temperature (°C), P = daily percentage of total annual daylight hours (%), and K= crop coefficient.

Crop coefficient was estimated based on the phenological stage of 100-day corn *(Zea mays L.)* using the relationship given by Seeley and Spoden (1982). The value of K for various stages of corn growth was taken from Seeley and Spoden (1982) and is given in Figure 2-1. Phenological stage of crop was identified using the cumulative growing degree days since planting and the relationship (Figure 2-2) given by Bergsrud et al. (1982).

Input for our calculation included 41 years (1950-1990) of daily precipitation, and daily maximum and minimum air temperatures for the growing season (April 1-November 31) at fifteen locations in and around the Central Sands of Minnesota (Figure 2-3). Soil thawing and crop planting were set constant on 5 April and 10 May of each year, respectively. Simulation of percolation started with the soil thawing date. Corn harvesting was set on 20 September and soil froze on 5 December of each year. Percolation was calculated daily using Eq. [1]. Rainfall, evapotranspiration and percolation data were summarized in terms of probabilities at various times of the growing season. Probabilities were calculated using Eq. [3] after the data have been arranged in a descending order.

$$Prob = \frac{n}{N + 1} \qquad [3]$$

where Prob = exceedance probability (%), n = position of a given value of the parameter in the descending order, and N = total number of years in the simulation (41).

Percolation losses were calculated with and without irrigation for soils with WHC varying from 2.5, 5.0, 7.5, 10.0 and 12.5 cm. For the irrigation treatment, irrigation was applied when the soil water deficit (percent of WHC remaining in soil) was greater than the irrigation trigger factor (Figure 2-4). The two other irrigation scenarios used were: (1) a 30% water depletion before irrigation is applied, and (2) a 60-40-60% depletion before an irrigation is applied. The 30 % water depletion means to set irrigation strategy to apply water whenever 30% of the WHC has been depleted at any time during the growing season. The 60-40-60% water depletion means to set irrigation strategy to apply water when 60, 40 or 60% of the WHC has been depleted from planting to 10th leaf, from 10th leaf to first dent and from first dent to the end of growth, respectively.

The probabilities were computed on a daily basis in order to identify the dates when leaching losses were maximum.

RESULTS AND DISCUSSIONS

The probabilities of percolation were calculated for soils with 2.5, 5.0, 7.5, 10.0, and 12.5 cm water holding capacities. At 50% probability (median year), peak weekly percolation at Wadena, MN, was around 1.4 cm for soils having a water holding capacity of 2.5 cm. For the same soil, peak monthly percolation losses were 7.5 cm.

In Figures 2-5 and 2-6 are given the components of a daily water balance with and without irrigation in 1989 for soils with water holding capacities of 5 and 10 cm at Wadena, MN. Based on Eq. [3], the calculated annual percolation in 1989 at Wadena represented an annual percolation at a probability of 50% (median year). Figures 2-5 and 2-6 show that the growing season can be divided into three percolation periods: planting to silking (April to June), silking to harvest (June to September), and harvest to soil freezing (September to November). Forty to fifty percent the annual percolation occurs from planting to silking and almost all of this percolation is from rainwater. Fertilizer is applied for corn from planting to silking. Since precipitation amount and timing can not be controlled, fertilizer management may be the only option to minimize leaching of nitrate during this period. Some of the fertilizer management options could be splitting and applying the fertilizer in several applications and using ammonia as a sources N fertilizer.

Percolation losses from silking to harvest (June to September) are minimal (Figures 2-5 and 2-6) if conservative irrigation scheduling schemes are followed, i.e., irrigation amounts are never more than the soil water deficit. However, in spite of a conservative irrigation schedule, there are some days when percolation will occur. These periods correspond to those times when rainfall occurs right after an irrigation. Since irrigation has to be applied to meet crop water needs, and since precipitation can not be controlled, the best way to minimize nitrate leaching from silking to harvest could be through smaller but more frequent application of irrigation. In this scheme some soil water holding capacity will remained unfilled for storage of rain that may occur right after irrigation. Irrigation through drip irrigation systems is another possibility to minimize nitrate leaching during this period. Since drip irrigation is localized, it only supplies water to a small soil volume thus leaving a relatively large volume of soil for storage of rain water.

Percolation losses during the post harvest (September to November) period are also a result of rainfall in excess of the soil water holding capacity (Figures 2-5 and 2-6). Since precipitation can not be controlled, the best management practice for this period will be to immobilize residual nitrogen that may be left from the growing season. This may be accomplished through seeding of a cover crop before the fall harvest.

The components of the annual water balance from 1950-1990 for Wadena, MN are shown in Figures 2-7 and 2-8. Percolation losses follow the precipitation pattern with or without irrigation. In other words, the greater the precipitation for a given year, the higher were the percolation losses. Effects of various irrigation scenarios on annual percolation losses are minimal. This is primarily because the irrigation amounts were never allowed to exceed the soil water deficit on any given day.

Annual percolation, precipitation, and ET for soils having a water holding capacities of 2.5, 5.0, 7.5, 10.0 and 12.5 cm at various probabilities with and without irrigation for 15 locations in the Central Sands of Minnesota are listed in the Table 2-1. Similar probabilities for 5 out of 15 locations for two other irrigation schemes, a 30 % water depletion before irrigation is applied and a 60-40-60% depletion before an irrigation is applied are shown in Table 2-2. The data in the Tables 2-1 and 2-2 show that as much as 47 cm of percolation (Grand Meadow, MN) is possible in the Central Sands of Minnesota, if the soil water holding capacity is 2.5 cm. However, the probability of such an event is only 10%. At 50% probability (median year), percolation losses vary from 12 cm (Crookston, MN) to 28 cm (Grand Meadow, MN) from soils with a water holding capacity of 2.5 cm. As expected, with an increase in the soil water holding capacity the percolation losses decrease. The two irrigation schemes, a constant 30% depletion and a 60-40-60% depletion based on growth stages, have a minor effect on the percolation losses. This may be partially because in any of the irrigation schemes, water addition is never more than the deficit needed to bring the soil to its soil capacity. Minor differences between various irrigation schemes are due to the differences from rain that may have occurred following an irrigation.

Annual percolation losses at 10 and 50% probabilities for soils having water holding capacities of 5 and 10 cm at various Minnesota locations with and without irrigation are mapped in Figures 2-9 and 2-10. In general, the percolation losses decrease from east to west and south to north for a soil with a given water holding capacity. Also, at any given probability, the percolation losses are slightly higher when irrigated than without irrigation. As expected, percolation decreases if the soils have a higher water holding capacity.

CONCLUSIONS

Daily, weekly and monthly percolation losses from soil of various water holding capacities followed the trends of precipitation distribution in MInnesota. Peak weekly percolation losses in central Minnesota occurred around the middle of June. At 50% probability, annual percolation losses were about 20 cm and 12 cm for soils having a water holding of 5.0 and 10.0 cm, respectively. Some percolation also occurred from silking to harvest even under optimal irrigation schedules, although most of this percolation was limited to days when rain followed an irrigation.

Based on the long-term daily, weekly, monthly, and yearly percolation data, the growing season can be divided into three periods for irrigation and fertilizer management. In the first period (April-June), nitrogen losses can be minimized by managing the source and timing of fertilizer application. In the second period (June to September), nitrogen losses can be minimized by managing the amount and timing of irrigation. In the third period (September-November), nitrogen losses can be minimized by growing a cover crop that will tie-up the residual nitrogen from the growing season.

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REFERENCES

Bergsrud, F. G., J. A. Wright, H. D. Werner, and G. J. Spoden. 1982. Irrigation system design capacities for west central Minnesota as related to the available water holding capacity and irrigation management. NCR82-01, No. Central Region Ann. Meeting, Amer. Soc. of Agri. Eng..

Blake, G. R., E. R. Allred, C. H. M. van Bavel and F. D. Whisler. 1960. Agricultural drought and moisture excesses in Minnesota. Technical Bulletin 235, Minn. Agri. Expt. Sta. and USDA-ARS.p36.

Hallberg, G. R., R. D. Libra, E. A. Bettis, and B. E. Hoyer. 1984. Hydrogeologic and water quality investigations in Big Spring Basin, Clayton County, Iowa: 1983 water year. Open-file Rep. No. 84-4. Iowa Geological Survey.

Klaseus, T. G., G. C. Buzicky, and E. C. Schneider. 1988. Pesticides and groundwater: Survey of selected Minnesota wells. Report for the Legislative Commission on Minnesota Resources, Minnesota Dept. of Health and Minnesota Dept. of Agriculture.

Nielsen, E. G. and L. K. Lee. 1987. The magnitude and costs of groundwater contamination from agriculture chemicals: A national perspective. Agricultural Economic Rep. No. 576, U.S. Dept. of Agriculture.

Seeley, M., and G. J. Spoden. 1982. Background of crop water use models. Special report 100, Agri. Extension Service, University of Minnesota, St. Paul.

Table 2-1. Annual percolation, precipitation, and evaportranspiration (ET) as a function of soil water holding capacity (WHC) at various probabilities in Minnesota.

		Site=Crookston					Site=Bemidji				
		Probabilities					Probabilities				
Irr†	WHC	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
		Annual percolation (cm)					Annual percolation (cm)				
I-0	2.5	20.9	17.2	16.7	14.4	12.2	29.1	25.9	22.9	20.6	17.6
	5.0	13.3	11.2	9.4	8.3	6.5	22.9	18.8	16.0	14.5	11.6
	7.5	9.0	6.4	5.0	4.1	2.7	18.1	14.4	11.7	10.3	6.7
	10.0	6.4	3.6	2.3	1.1	0.2	13.4	11.3	7.8	5.5	3.0
	12.5	3.0	1.0	0.0	0.0	0.0	9.8	7.3	5.2	2.8	0.5
I=1	2.5	23.4	20.1	18.4	16.8	13.9	31.4	28.9	25.6	23.9	20.2
	5.0	16.7	12.7	11.2	9.4	8.6	24.5	20.6	18.6	17.1	12.8
	7.5	11.9	9.3	7.5	6.5	4.8	21.2	16.5	14.1	12.3	9.6
	10.0	10.2	6.5	4.9	4.0	2.0	16.7	11.9	9.6	7.7	4.8
	12.5	7.6	3.9	2.7	1.2	0.0	10.5	9.2	8.0	5.2	3.1
		Precipitation, cm					Precipitation, cm				
		55.3	51.1	49.6	48.4	46.0	66.9	62.1	59.6	55.7	54.4
		ET, cm					ET, cm				
		61.7	60.2	59.3	57.9	56.5	56.2	55.1	52.1	51.1	50.4

† I=0: without irrigation.
I=I: with irrigation.

Table 2-1. Continued

		Site = Detroit Lakes					Site=Wadena				
		Probabilities					Probabilities				
Irr.	WHC	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
		annual percolation (cm)					annual percolation (cm)				
I-0	2.5	29.6	25.9	23.4	19.7	16.8	32.7	27.3	25.4	23.5	20.5
	5.0	22.3	19.0	15.7	13.1	10.9	26.6	19.9	17.9	15.9	13.8
	7.5	19.3	16.0	11.6	9.2	6.1	21.5	14.9	14.0	10.8	7.6
	10.0	16.7	11.9	8.1	4.8	3.5	16.6	11.3	9.0	6.5	4.8
	12.5	14.2	9.2	5.4	2.0	0.9	12.5	7.8	5.1	2.7	1.8
I-1	2.5	32.4	28.3	26.0	21.2	19.4	34.7	28.8	27.0	25.5	22.2
	5.0	24.2	19.2	17.8	15.5	14.0	27.7	21.6	19.0	17.3	15.9
	7.5	19.6	16.2	13.1	11.1	8.2	23.1	16.9	15.9	12.6	10.5
	10.0	17.9	14.2	8.9	8.2	5.3	17.8	14.2	11.4	10.1	7.2
	12.5	14.3	10.7	7.8	5.4	3.0	16.2	9.9	6.7	5.7	3.6
		Precipitation, cm					Precipitation, cm				
		69.8	62.3	59.2	56.3	53.3	71.9	69.4	63.5	59.6	55.3
		ET, cm					ET, cm				
		57.9	56.5	54.5	52.2	51.7	59.3	56.2	56.7	55.3	54.8

† I=0: without irrigation.
I=I: with irrigation.

Table 2-1. (continued)

Irr†	WHC	Site=Grand Rapids: Probabilities 10%	20%	30%	40%	50%	Site=Virginia: Probabilities 10%	20%	30%	40%	50%
		annual percolation (cm)					annual percolation (cm)				
I-0	2.5	32.9	27.9	26.5	25.5	23.6	33.2	30.2	28.9	26.7	22.9
	5.0	25.8	22.6	20.1	19.0	17.4	26.6	24.7	22.9	19.5	17.7
	7.5	21.6	17.2	15.0	13.4	11.8	21.6	19.6	17.6	14.6	12.7
	10.0	18.8	12.1	10.4	9.4	7.6	18.0	15.1	13.5	10.2	8.2
	12.5	13.7	7.9	7.3	5.5	4.0	15.3	11.2	10.1	7.6	3.9
I-1	2.5	34.7	29.5	28.1	27.6	25.8	35.1	31.3	29.5	28.4	24.8
	5.0	27.5	24.9	22.1	21.1	16.4	27.1	26.4	24.6	21.7	19.3
	7.5	22.2	19.6	17.6	15.0	13.1	23.8	21.2	19.7	16.4	12.8
	10.0	19.5	15.5	12.0	10.4	9.5	18.4	16.3	14.5	13.0	10.0
	12.5	15.8	10.6	9.1	7.4	6.1	15.9	13.3	10.9	9.8	7.7
		Precipitation, cm					Precipitation, cm				
		71.3	68.4	65.2	62.0	57.7	72.0	70.0	65.9	63.7	59.5
		ET, cm					ET, cm				
		56.0	54.3	52.7	51.9	50.6	54.4	52.5	51.6	50.4	49.5

† I=0: without irrigation.
I=I: with irrigation.

Table 2-1. (continued)

Irr†	WHC	Site=Little Falls: Probabilities 10%	20%	30%	40%	50%	Site=Mora: Probabilities 10%	20%	30%	40%	50%
		annual percolation (cm)					annual percolation (cm)				
I=0	2.5	31.4	27.4	23.0	21.4	17.6	38.0	32.1	30.1	26.7	23.1
	5.0	25.0	18.6	15.6	14.3	10.7	31.8	25.7	23.0	19.3	15.6
	7.5	19.9	14.9	11.7	10.0	5.5	27.2	20.5	18.0	14.2	11.6
	10.0	16.2	11.7	8.6	6.7	3.0	22.1	15.7	13.4	9.3	6.3
	12,5	12.3	9.2	6.3	4.2	0.4	17.0	12.6	10.1	6.6	5.8
I=I	2.5	33.5	31.5	26.5	23.8	21.1	39.6	35.6	32.8	29.1	24.9
	5.0	26.3	22.0	17.7	15.6	12.4	34.1	26.4	24.5	20.4	18.7
	7.5	21.8	17.2	14.0	11.5	7.9	26.1	21.8	21.0	15.6	12.7
	10.0	18.1	14.0	10.7	7.3	5.2	24.3	17.9	15.9	14.3	10.7
	12.5	14.1	12.4	7.6	6.1	3.6	19.3	15.8	13.4	10.3	6.5
		Precipitation, cm					Precipitation, cm				
		70.5	67.4	64.7	62.6	56.0	80.2	73.9	71.3	63.0	62.7
		ET, cm					ET, cm				
		64.5	62.0	61.3	60.4	59.3	61.3	60.4	58.7	57.4	56.4

† I=0: without irrigation.
I=I: with irrigation.

Table 2-1. (continued)

Irr†	WHC	Site=Willmar 10%	20%	30%	40%	50%	Site=Minneapolis 10%	20%	30%	40%	50%
		annual percolation (cm)					annual percolation (cm)				
I=0	2.5	35.5	31.5	27.6	23.6	20.5	34.8	27.7	24.0	19.6	15.8
	5.0	27.3	24.4	20.2	17.2	12.5	26.7	22.6	16.1	11.6	8.7
	7.5	22.2	19.3	15.1	11.1	8.6	21.6	19.3	11.0	8.0	5.8
	10.0	17.2	16.2	10.0	7.2	4.5	17.5	15.3	6.8	4.1	2.7
	12.5	14.3	12.1	5.1	4.4	1.9	14.8	10.7	4.2	1.4	0.1
I=1	2.5	36.1	32.5	30.1	26.5	22.8	38.2	30.8	24.9	21.6	16.5
	5.0	31.6	24.6	22.2	18.7	14.8	29.4	24.1	18.6	12.7	9.9
	7.5	24.5	20.4	18.9	15.9	12.0	24.1	19.3	13.7	9.3	6.2
	10.0	20.6	16.5	14.8	11.5	5.8	20.0	16.1	8.6	6.8	3.4
	12.5	16.7	13.2	11.2	8.5	3.1	17.6	13.7	9.1	4.3	1.2
		Precipitation, cm					Precipitation, cm				
		80.3	73.7	70.3	65.7	60.3	77.7	71.4	64.8	61.5	56.1
		ET, cm					ET, cm				
		66.5	65.9	64.6	63.5	62.2	68.8	66.0	66.2	65.3	64.5

† I=0: without irrigation.
I=I: with irrigation.

Table 2-1. (continued)

Irr†	WHC	Site=Waseca 10%	20%	30%	40%	50%	Site= Worthington 10%	20%	30%	40%	50%
		annual percolation (cm)					annual percolation (cm)				
I=0	2.5	38.1	32.3	29.5	26.9	23.9	32.6	30.4	27.7	24.3	18.8
	5.0	30.2	24.4	22.2	18.6	15.4	26.3	22.4	20.9	17.1	12.3
	7.5	23.6	20.4	17.9	13.5	10.4	21.4	17.2	15.8	11.8	6.3
	10.0	18.9	16.1	13.6	9.4	6.5	16.7	13.4	10.7	7.9	3.4
	12.5	14.3	12.1	9.5	6.8	4.0	13.4	9.3	6.0	3.8	0.8
I-1	2.5	41.2	35.0	31.9	29.2	27.5	34.8	32.1	30.3	26.1	20.0
	5.0	31.4	27.1	24.4	22.5	18.9	26.7	24.8	23.5	20.2	13.2
	7.5	25.5	21.1	19.4	15.4	13.2	21.7	20.0	17.9	14.4	6.9
	10.0	21.1	18.2	15.3	11.1	8.7	18.1	16.0	11.3	8.3	5.3
	12.5	17.2	15.4	12.4	8.0	5.9	16.1	11.9	6.9	5.4	2.7
		Precipitation, cm					Precipitation, cm				
		64.4	79.4	70.0	68.2	65.1	71.5	69.0	66.5	61.7	57.0
		ET, cm					ET, cm				
		66.4	64.3	63.7	63.1	61.9	64.2	63.5	62.8	62.5	60.5

† I=0: without irrigation.
I=I: with irrigation.

Table 2-1. (continued)

Irr†	WHC	Site= Farmington 10%	20%	30%	40%	50%	Site= Grand Meadow 10%	20%	30%	40%	50%
		annual percolation (cm)					annual percolation (cm)				
I=0	2.5	36.1	36.4	28.0	24.3	21.6	44.9	38.9	34.3	30.2	27.5
	5.0	29.6	26.8	21.6	17.9	12.7	36.0	31.2	26.1	22.8	19.8
	7.5	23.8	19.6	16.3	11.8	8.6	32.6	24.5	18.7	17.8	14.7
	10.0	18.7	15.2	11.4	8.2	4.5	27.7	19.8	15.3	13.6	10.9
	12.5	14.9	10.7	7.6	5.7	1.9	22.6	14.9	12.3	10.0	7.7
I-1	2.5	40.4	36.8	30.7	27.2	25.0	47.1	41.7	37.4	31.4	28.3
	5.0	33.0	30.1	22.2	18.9	15.9	39.9	33.5	28.4	24.7	20.3
	7.5	25.8	23.0	19.0	15.4	11.5	33.3	28.5	21.9	18.8	15.0
	10.0	23.2	17.9	14.7	11.8	7.6	28.3	21.8	16.9	14.9	11.8
	12.5	17.0	14.1	10.8	7.6	3.5	26.0	19.2	15.8	12.5	10.0
		Precipitation, cm					Precipitation, cm				
		82.5	80.8	72.6	66.4	59.0	87.6	83.4	78.8	72.5	68.1
		ET, cm					ET, cm				
		66.5	65.9	65.1	63.6	63.3	63.4	62.3	61.5	61.0	59.6

† I=0: without irrigation.
I=I: with irrigation.

Table 2-1. (continued)

Irr†	WHC	Site= Morris 10%	20%	30%	40%	50%
		annual percolation (cm)				
I=0	2.5	30.2	27.00	23.9	20.7	17.5
	5.0	22.4	19.50	16.6	13.9	11.0
	7.5	16.8	14.50	12.1	9.7	7.3
	10.0	12.2	10.30	8.5	6.6	4.8
	12.5	8.3	7.00	5.6	4.4	3.0
I=1	2.5	39.8	36.10	32.5	26.8	25.1
	5.0	27.3	24.20	21.0	17.7	14.6
	7.5	20.7	17.90	15.0	12.3	9.6
	10.0	15.4	13.30	10.9	6.6	6.4
	12.5	11.3	9.50	7.7	5.9	4.3
		Precipitation, cm				
		69.6	65.30	60.9	56.4	52.0
		ET, cm				
		64.2	63.00	61.7	60.4	59.1

† I=0: without irrigation.
I=I: with irrigation.

Table 2-2. Annual percolation, precipitation, and potential evaportranspiration (PET) as a function of soil water holding capacity (WHC) at various probabilities for two different irrigation strategies.

Site=Bemidji

	Irrigation strategies†									
	30% soil water depletion					60%-40%-60% soil water depletion				
	Probabilities									
WHC	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
	Annual percolation, cm									
2.5	33.2	28.7	26.8	23.6	20.8	32.3	28.3	26.0	22.9	18.6
5.0	24.6	23.4	19.8	17.2	13.3	25.2	21.5	18.6	16.0	12.8
7.5	19.8	1.8.0	13.9	12.1	10.3	19.8	17.7	13.6	11.6	10.1
10.0	18.8	4.7	9.9	7.8	6.1	17.6	13.0	10.2	7.7	5.7
12.5	13.9	9.1	7.0	5.9	4.6	13.2	8.6	6.8	5.2	3.1
	Precipitation, cm									
	68.9	62.1	59.6	55.7	54.4	68.9	62.1	59.6	55.7	54.4
	PET, cm									
	56.2	55.1	52.1	51.1	50.4	56.2	55.1	52.1	51.1	50.4

†: The 30 % water depletion irrigation strategy applied water whenever 30% of the WHC has been depleted. The 60-40-60% water depletion irrigation strategy applied water when 60, 40 or 60% of the soil water has been depleted from planting to 10th leaf, from 10th leaf to first dent and from first dent to the end of growth, respectively.

Table 2-2. Continued.

Site=Virginia

	Irrigation strategies†									
	30% soil water depletion					60%-40%-60% soil water depletion				
	Probabilities									
WHC	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
	Annual percolation, cm									
2.5	35.9	32.4	30.8	29.3	26.4	35.5	31.5	30.4	29.3	24.6
5.0	29.5	26.9	24.7	22.7	19.0	28.2	26.8	25.4	21.6	18.5
7.5	26.0	22.5	20.0	17.8	14.7	24.6	22.6	21.2	17.3	14.7
10.0	19.8	18.2	17.1	12.9	11.8	18.4	17.4	16.1	12.5	10.0
12.5	17.4	15.9	12.0	10.7	7.7	16.1	14.2	11.2	9.8	7.5
	Precipitation, cm									
	68.9	62.1	59.6	55.7	54.4	68.9	62.1	59.6	55.7	54.4
	PET, cm									
	56.2	55.1	52.1	51.1	50.4	56.2	55.1	52.1	51.1	50.4

†: The 30 % water depletion irrigation strategy applied water whenever 30% of the WHC has been depleted. The 60-40-60% water depletion irrigation strategy applied water when 60, 40 or 60% of the soil water has been depleted from planting to 10th leaf, from 10th leaf to first dent and from first dent to the end of growth, respectively.

Table 2-2. Continued.

Site=Wadena

	Irrigation strategies†									
	30% soil water depletion					60%-40%-60% soil water depletion				
	Probabilities									
WHC	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
	Annual percolation, cm									
2.5	37.0	30.2	27.4	25.8	23.5	35.2	29.4	26.9	25.4	22.8
5.0	28.6	23.0	18.0	17.0	14.9	28.0	21.6	19.0	17.3	15.9
7.5	24.7	17.7	16.4	13.2	11.2	26.1	16.6	15.0	12.3	8.7
10.0	20.5	14.0	11.6	8.7	7.6	19.8	13.5	10.3	8.1	6.1
12.5	16.1	9.7	6.8	5.9	5.3	13.9	9.7	5.6	4.4	3.5
	Precipitation, cm									
	71.9	69.4	63.5	59.6	55.3	71.9	69.4	63.5	59.6	55.3
	PET, cm									
	59.3	58.2	56.7	55.3	54.8	59.3	58.2	56.7	55.3	54.8

†: The 30 % water depletion irrigation strategy applied water whenever 30% of the WHC has been depleted. The 60-40-60% water depletion irrigation strategy applied water when 60, 40 or 60% of the soil water has been depleted from planting to 10th leaf, from 10th leaf to first dent and from first dent to the end of growth, respectively.

Site= Worthington

	Irrigation strategies†									
	30% soil water depletion					60%-40%-60% soil water depletion				
	Probabilities									
WHC	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
	Annual percolation, cm									
2.5	35.5	33.0	30.8	27.1	20.7	33.7	31.9	29.9	25.6	20.2
5.0	26.8	24.9	22.9	19.2	14.8	26.6	24.5	22.7	18.4	13.4
7.5	22.0	20.5	16.1	14.2	10.7	22.8	18.8	17.3	13.0	10.0
10.0	18.5	17.7	14.5	9.7	7.2	17.9	15.2	13.1	9.4	5.3
12.5	17.1	12.1	11.0	8.1	4.8	15.5	11.5	8.7	5.5	2.5
	Precipitation, cm									
	71.5	69.0	66.5	61.7	57.0	71.5	69.0	66.5	61.7	57.0
	PET, cm									
	64.2	63.5	62.8	62.5	60.5	64.2	63.5	62.8	62.5	60.5

†: The 30 % water depletion irrigation strategy applied water whenever 30% of the WHC has been depleted. The 60-40-60% water depletion irrigation strategy applied water when 60, 40 or 60% of the soil water has been depleted from planting to 10th leaf, from 10th leaf to first dent and from first dent to the end of growth, respectively.

Site= Grand Meadow

	Irrigation strategies†									
	30% soil water depletion					60%-40%-60% soil water depletion				
	Probabilities									
WHC	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%
	Annual percolation, cm									
2.5	46.5	43.1	37.8	32.9	29.5	47.4	41.7	36.2	32.3	29.3
5.0	41.7	33.9	28.9	25.0	21.7	39.4	33.5	28.5	24.5	20.1
7.5	35.2	28.3	24.2	22.3	17.3	34.6	27.2	22.9	19.9	16.5
10.0	28.9	21.9	18.0	15.3	11.8	28.8	21.1	16.7	15.0	10.9
12.5	26.2	22.9	16.7	12.5	10.4	24.2	18.8	15.0	12.6	9.2
	Precipitation, cm									
	87.6	83.4	78.8	72.5	68.1	87.6	83.4	78.8	72.5	68.1
	ET, cm									
	63.4	62.3	61.5	61.0	59.8	63.4	62.3	61.5	61.0	59.8

†: The 30 % water depletion irrigation strategy applied water whenever 30% of the WHC has been depleted. The 60-40-60% water depletion irrigation strategy applied water when 60, 40 or 60% of the soil water has been depleted from planting to 10th leaf, from 10th leaf to first dent and from first dent to the end of growth, respectively.

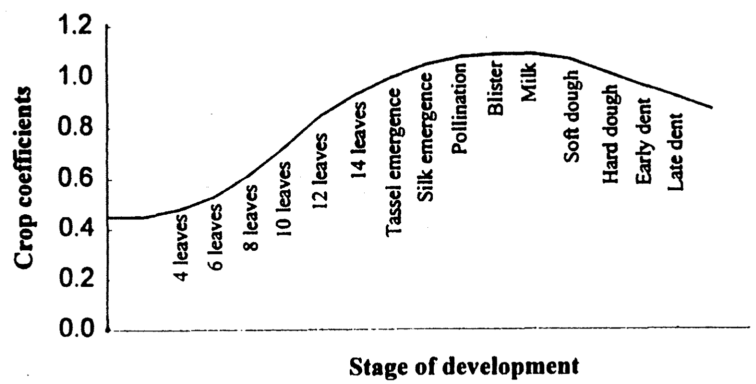

Figure 2-1. Blaney-Criddle crop coefficients for corn (after Seeley, M. and G. J. Spoden, 1982).

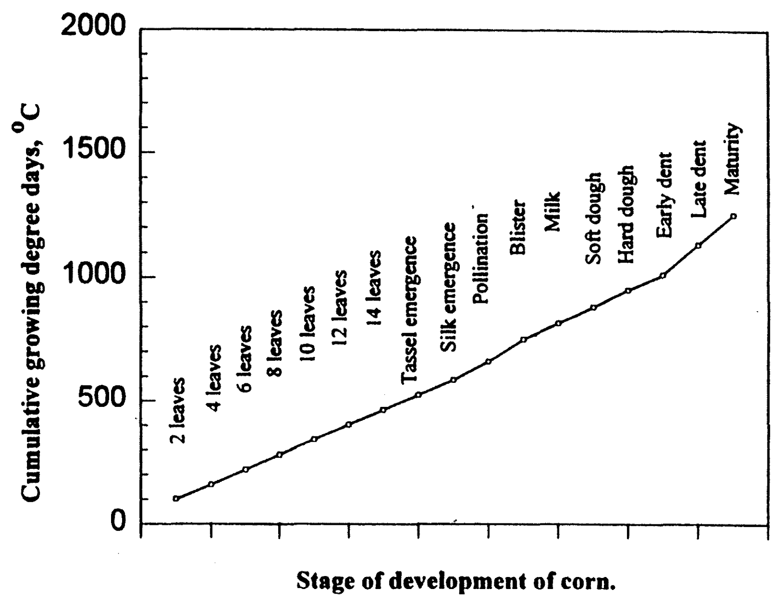

Figure 2-2. Relationship of stage of development for field corn to growing degree days (Base of 10°C, data from Bergsrud et al., 1982).

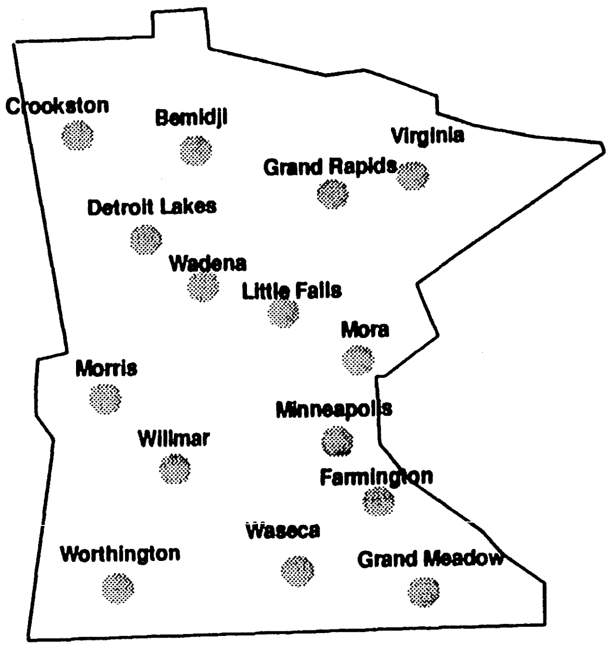

Figure 2-3. Meteorological stations used in this stduy.

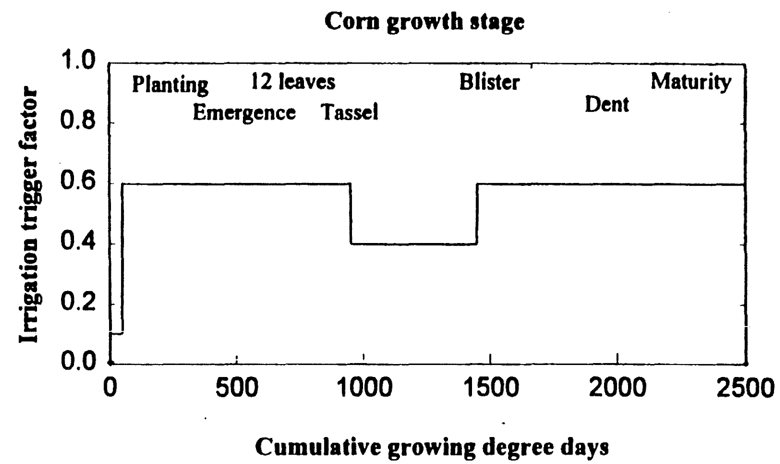

Figure 2-4. Irrigation trigger factor at various corn growth stages. Zero percent of irrigation trigger factor means 0% of soil water deficit before an irrigation is applied,whereas irrigation trigger factor of 1.0 means 100% of soil water deficit before an irrigation is applied.

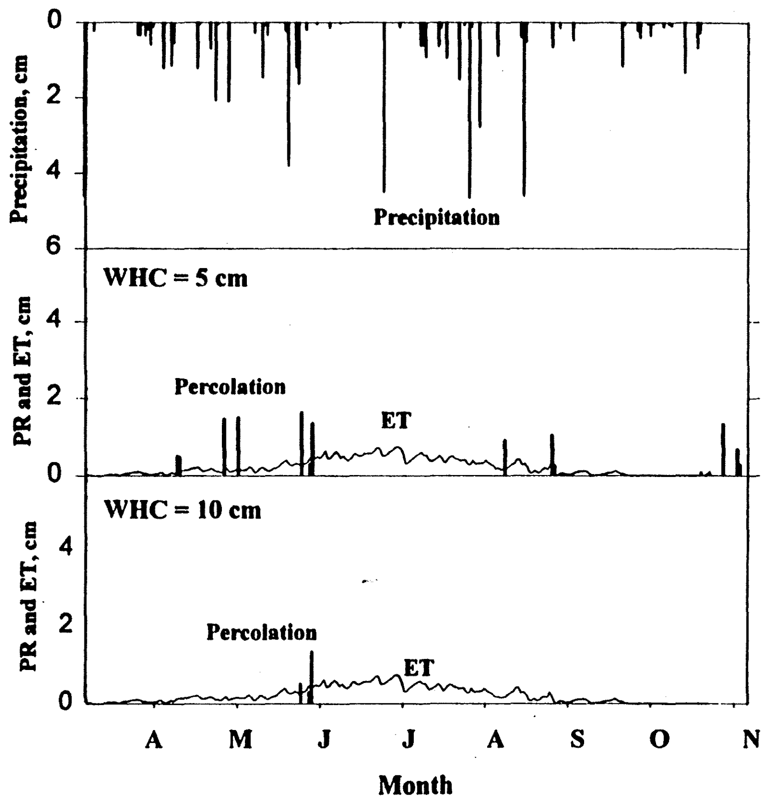

Figure 2-5. Precipitation and calculated water percolation (PR) and evapotranspiration (ET) at Wadena, MN during 1989 for non-irrigated soils with water holding capacities of 5 and 10 cm.

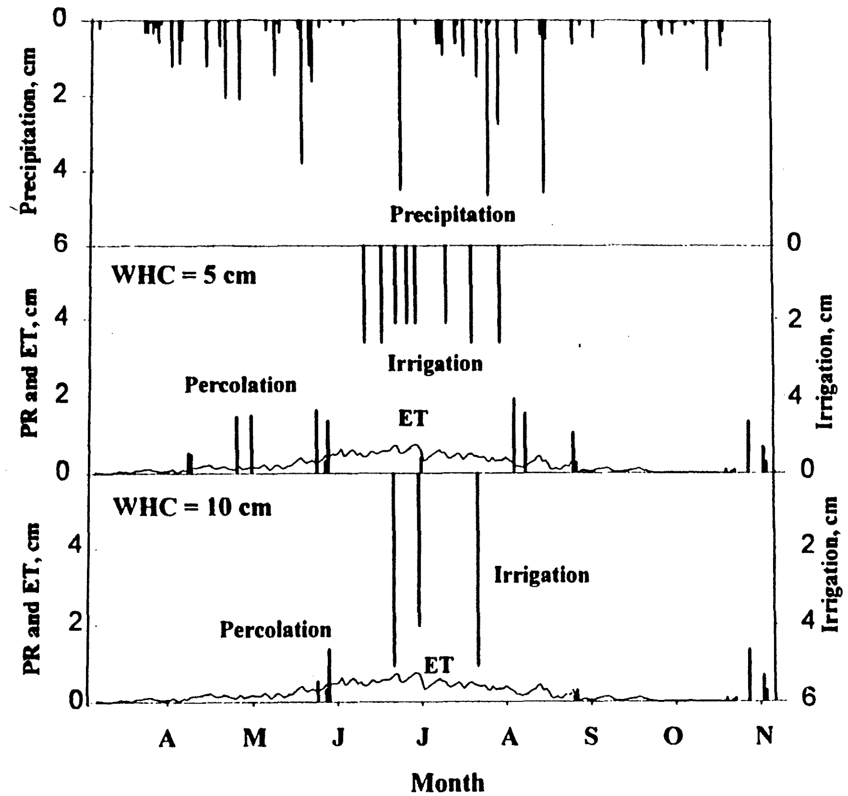

Figure 2-6. Precipitation and calculated water percolation (PR) and evapotranspiration (ET) at Wadena, MN during 1989 for irrigated soils with water holding capacities of 5 and 10 cm.

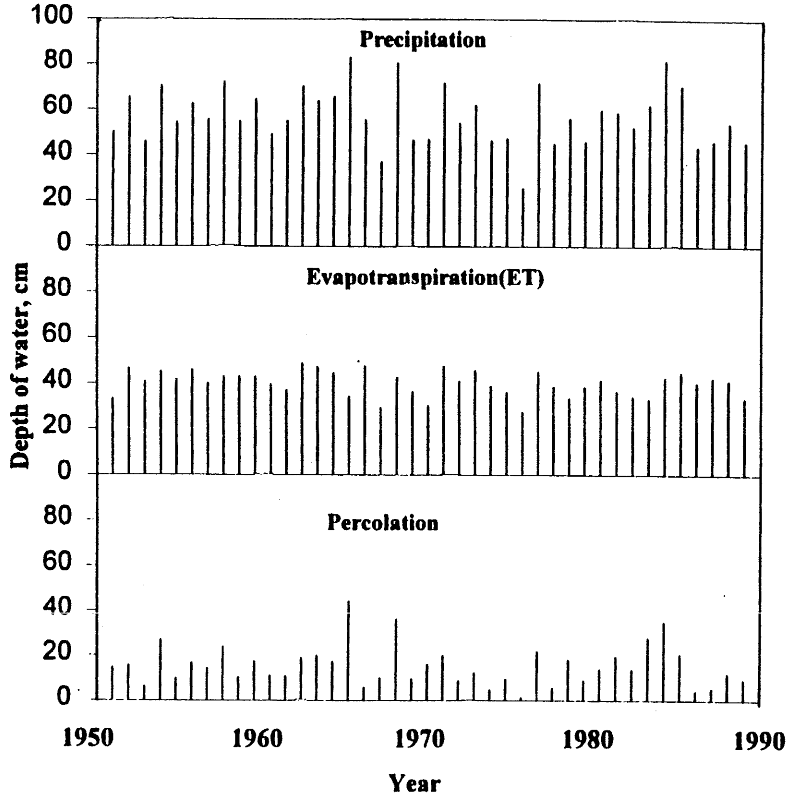

Figure 2-7. Annual percolation losses without irrigation from a soil with water holding capacity (WHC) of 5 cm at Wadena, MN (1950-1990).

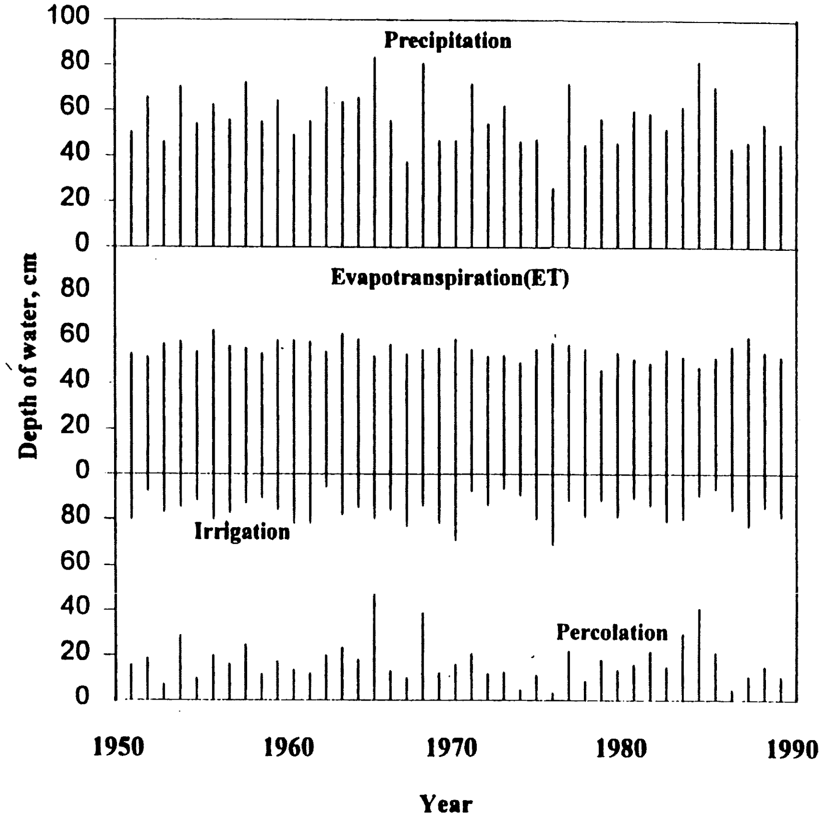

Figure 2-8. Annual percolation losses with irrigation from a soil with water holding capacity (WHC) of 5 cm at Wadena, MN (1950-1990).

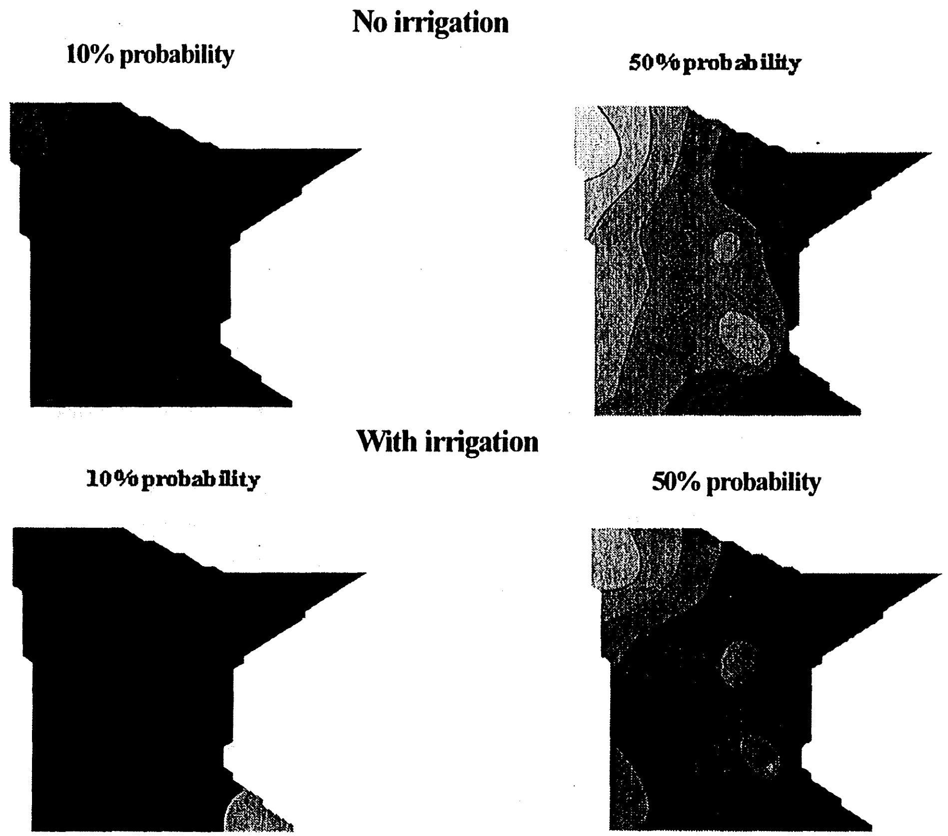

Figure 2-9. Calculated annual percolation (cm) from a Minnesota soil with a water holding capacity of 5 cm with and without irrigation at 10% and 50% (median year) of probabilities.

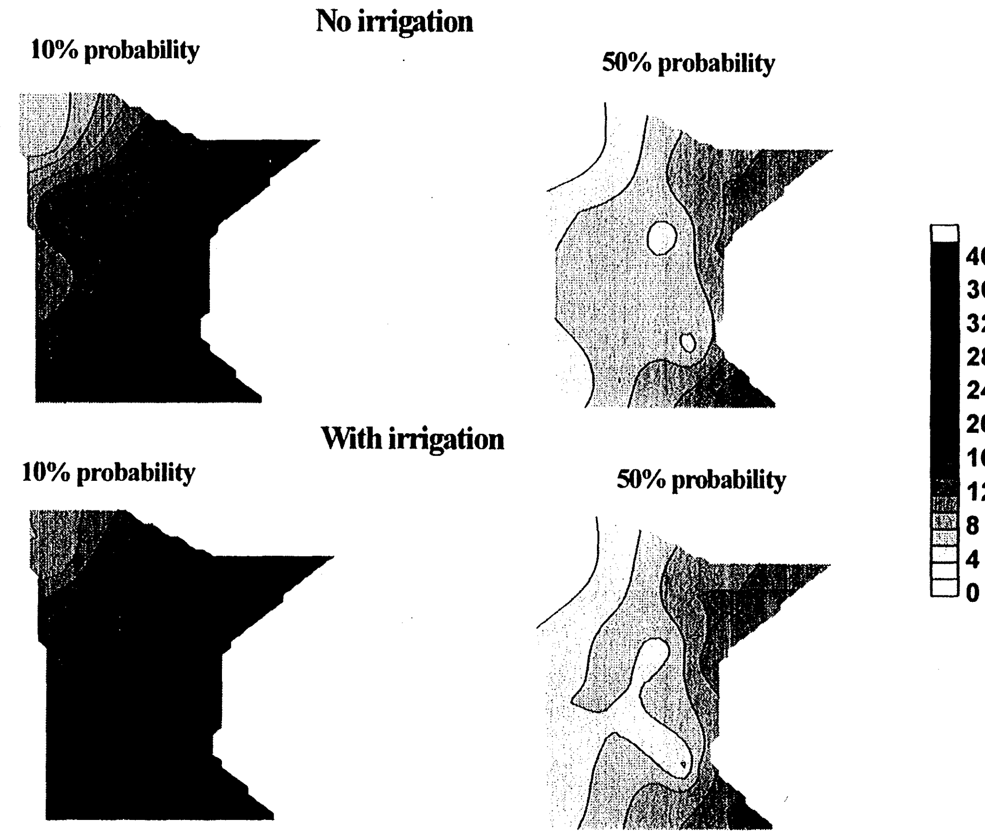

Figure 2-10. Calculated annual percolation (cm) from Minnesota soil with a water holding capacity of 10 cm with and without irrigation at 10% and 50% (median year) probabilities.

Chapter 3. RISK CHARACTERIZATION OF MINNESOTA OUTWASH SOILS TO NITRATE LEACHING

ABSTRACT

The paper discusses the validation of CERES-Maize model and how this model can be used to characterize the risk potential of soils to nitrate leaching. The validation is done against the experimental data on corn yield, N uptake and N leaching for four fertilizer application rates and two irrigation schedules on Verndale sandy loam (coarse loamy over sandy, mixed, frigid, Udic Argiboroll) during 1991 and 1992 at Staples, MN. In general, simulated values were close to the observed data. Simulation with 31 years of climatic data showed that N leaching is related to the amount of precipitation and weakly related to crop yield. Also, the N leaching in these soils is mainly caused by excess irrigation or unexpected rain that may occur right after irrigation. Therefore, it is concluded that in order to minimize N leaching, irrigation amount should be such that there is always some unfilled porespace in soil to capture the unforeseen rain that may occur after irrigation. A procedure is presented that characterizes the risk potential of these soils to N leaching based on the output results of long-term simulation of CERES-Maize. The procedure identifies fertilizer and irrigation management practices best suited for optimum yield and minimum N leaching for a given soil and a climatic probability.

INTRODUCTION

Nation wide, there is an increase in the number of studies documenting the presence of nitrate and pesticides in groundwater (Hallberg et al. 1984; CAST, 1985; Nielsen and Lee, 1987; Klaseus et al., 1988). In Minnesota, the survey by Klaseus et al. (1988) found elevated nitrate and pesticides in 43 and 33%, respectively, of the 500 wells tested in 51 counties. A significant number of these contaminated wells were in glacial outwash soils of Central Minnesota. A USGS study (Myette, 1984) of 124 wells in Hubbard, Morrison, Otter Tail and Wadena counties of Central Minnesota showed that nitrate concentration has been continuously increasing since the 1960's. In some wells, concentration of nitrate have exceeded the EPA drinking water standards of 10 mg l^{-1}.

The major soil factors contributing to nitrate leaching in outwash soils of Central Minnesota are their high permeability and low water holding capacity. Rainfall during spring and fall when the crop water and nitrogen needs are minimal is another major determinant to nitrate leaching. Rainfall that occurs right after an irrigation during the peak crop growth period (summer) also contributes to nitrate leaching (Pang et al., 1992; Sexton, 1993). Management factors affecting nitrate leaching are the timing and amount of irrigation and nitrogen.

Since soils and climatic factors can not be easily manipulated, the only option available to minimize nitrate leaching from these soils is through the management of irrigation and fertilizer. However to sustain the agriculture of the area, irrigation and fertilizer management scenarios must be such that they minimize leaching without significantly reducing crop yield.

In the past, recommendations for best management of fertilizer and irrigation have largely been based on crop yield data. Very little attention has been given to the potential of nitrate leaching under the recommended best management practices. Identification of best management practices that minimize nitrate leaching should not only consider the crop yield but also the extent of nitrate leaching covering several weather cycles. This type of information is generally lacking because the cost of setting up long term experiments and gathering this data is prohibitive.

Currently, there is very little long-term information available on the relationship between crop yield, nutrient uptake, and nitrate leaching for various nitrogen and irrigation management scenarios in the Central Sands of Minnesota. One of the inexpensive means of obtaining these data is through simulation models that integrate soil, climate and management information to predict crop growth, and availability and movement of nitrogen in the root zone. A few of these models are the Crop-Environment-Resource-Synthesis (CERES) Model for various crops, Leaching Estimation And Chemistry Model (LEACHM), Nitrogen Leaching and Economic Analysis Package (NLEAP), and Root Zone Water Quality (RZWQ) model. Although most of these models are based on the physical principles of water and nitrate movement in soil, these models need testing and validation before they can be extensively applied to a whole series of soils under different management and climatic conditions. The focus of this study was to test and validate the CERES-Maize model under the soil and climatic conditions of the Central Sands of Minnesota, and then identify the management practices that can minimize nitrate leaching. An additional objective of the study was to develop a procedure that can characterize the risk potential of soils to nitrate leaching under various management scenarios over several weather cycles. Since the outwash soils of North Central States are similar to the Central Sands of Minnesota, the best management practices and risk characterization procedure has a wider application.

Selection of a model depends upon the objectives under consideration. The model must be conceptually appropriate to the research in hand, it must have input requirements which can be practically met, and it must give reasonable predictions. The CERES-Maize model V2.10 (Jones et al., 1986) was chosen for this research because it meets these criteria. It has been extensively tested with many corn hybrids on many different soil types and for a range of climate (Wu et al., 1989; Cooter, 1990). It is well documented and, the weather inputs are routinely available. It also provides reasonable predictions of corn yields (Hodges et al., 1987). The CERES-Maize model is a user-oriented, daily-incrementing simulation model of maize growth, nitrogen uptake and nitrate leaching. The model also has the capability of simulating the impact of various irrigation management scenarios on crop yield and nitrate leaching.

With current emphasis on site specific farming, risk indices linked with a soil survey data base could be a valuable tool in prescribing management practices that maximize yield and minimize nitrate leaching. Since the concept of site specific farming is relatively new, there is limited literature on site risk characterization procedures based on the long-term climatic data. Watts and Martin (1981) used a computer model to assess the effect of water and nitrogen management on nitrate leaching in Valentine very fine sand at North Platte, Nebraska. Their simulation included three cropping seasons covering above normal, normal, and below normal rainfalls. These authors concluded that irrigation amount, nitrogen source, nitrogen amount and timing of nitrogen application can all have significant effects on reduction of nitrate leaching in their soil. Also, nitrate losses can not be reduced to zero because of the early season percolation from natural rainfall. Recently, Khakural and Robert (1993) proposed a soil nitrate leaching index based on the simulation results of LEACHM-N. The authors used the normal and above normal precipitation to develop nitrate leaching indices. In their simulation, all the crop input parameters including nitrogen uptake were kept constant irrespective of soil nitrogen availability. Also, the LEACHM-N model used in their simulation did not account for the contribution of mineralized N from the organic matter. Since organic matter in soil of the North Central States is relatively high and could be an important source of nitrate leaching, nitrate leaching indices based on zero N mineralization will be in error. Since a combination of precipitation, temperature and other factors control the nitrogen uptake, nitrogen mineralization and thus nitrate leaching, an above normal and normal precipitation year as inputs will be inadequate in assessing the true nitrate leaching potentials of a given soil. It is better that a long-term climatic information is used in simulation study and the risk indices are presented at various climatic probabilities.

This study present a procedure that characterize the risk potential of soils to nitrate leaching for various management scenarios over several climatic cycles. The simulation data base for nitrate leaching consider the variable crop yield and thus variable nitrogen uptake. Also, the contribution from organic matter mineralization are included in the simulations.

PROCEDURES

Validation of the CERES-Maize model reported in this manuscript is based on the 1991 and 1992 experimental data on irrigation and fertilizer management trials conducted at the Staples Irrigation Center, Staples, MN by Sexton (1993). The validated parameters are crop yield, nitrogen uptake and nitrate leaching.

Field Experiment

Briefly, the experiment was conducted on a Verndale sandy loam (coarse loamy over sandy, mixed, frigid Udic Argiboroll) with less than 2% slope. The crop rotation was corn (*Zea mays L.*, Pioneer 3921 hybrid) and potato (*Solanum tuberosum*, Russet-Burbank variety).

Date of sowing, planting density, irrigation amounts, crop growth parameters , and corn yield for the above experiment are summarized in Table 3-1. Two irrigation schedules were used: schedule #1 which irrigated at a fixed amount to field capacity or slightly higher water contents and schedule #2 which practiced deficit irrigation with varied irrigation input and timing based on the crop growth stage (variable rate). Timing of all irrigations was determined using the checkbook method of Wright and Bergsrud (1986). Nitrogen sources were urea $CO(NH_2)_2$ applied at various rates ranging from 0 to 284 kg N ha^{-1} and two turkey manure treatments. The data reported in this paper only deals with the urea treatments. The dates and amounts of urea application are listed in Table 3-2.

Suction cup samplers were used to obtain soil water samples for nitrate analysis. Matric potentials were measured using tensiometers. Both tensiometer and suction cup samplers were installed at 60 cm in 1991 and 90 cm in 1992. Details on the sampling protocol and nitrate analysis are given in Sexton (1993).

Simulation Procedures

For the validation purpose, the CERES-Maize model simulated corn growth, N uptake and nitrate leaching for two irrigation and four fertilizer treatments listed in Tables 3-1 and 3-2. Inputs included the daily weather information of maximum and minimum air temperature, solar radiation, and precipitation, soil hydraulic properties, and management information such as irrigation amounts and dates (Figures 3-1 and 3-2) and fertilizer amounts and dates (Table 3-2).

Values of the genetic parameters for the hybrid Pioneer 3921 are listed in Table 3-3. The thermal time (growing degree days) from seed emergence to the end of juvenile stage (P1) in the CERES-Maize model (Table 3-3) was set equal to that required to produce the observed date of silking (Table 3-4). This validation procedure was suggested by one of the model developers (Ritchie J. 1993. Crop and Soil Science Department of Michigan State University, Personal Communication). This ensured that CERES-Maize model gave the right performance regarding the crop growth. This has been done for 1991 and 1992. The photoperiod sensitivity coefficient (P_2) was given the value of zero as suggested by Jones and Kiniry (1986) for Northern Corn Belt hybrids. The thermal time from silking to physiological maturity or black layer formation (P_5) in the CERES-Maize model (Table 3-3) was set equal to that required to produce the observed date of black layer. Maximum kernel number per plant (G_2) and potential kernel growth rate (G_3) in Table 3-3 were taken from Jones et al. (1986) for corn hybrids grown in the Northern Corn Belt states.

The values of the lower limit of the available soil water (LL), drained upper limit of the available soil water (DUL) and saturated water content (SAT) were estimated from moisture retention curves measured in the laboratory on undisturbed soil cores taken from the site (Sexton, 1993). The lower and upper limits of the available soil water were taken as water content at soil matric potential of -1500 and -33 kPa, respectively. The drainage parameter SWCON which is equivalent to profile hydraulic conductivity (day^{-1}) was set equal to 0.60. This value was estimated using the procedure of Ritchie and Crum (1989) and is based on drainage and permeability classes defined for this soil in the Wadena County, MN Soil Survey (SCS, 1991).

Three of four replications in Sexton's 1991 experiments were on plots where lupines (*Lupinus albus*) had been grown in 1990. This previous crop of lupines appeared to contribute significant amounts of N to the 1991 corn crop (Sexton, 1993). The contribution of lupines was included in simulations by increasing the amount of crop residue and by decreasing its carbon to nitrogen (C:N) ratio. Ayisi (1991) suggested that the previous crop of lupines appeared to contribute 50-70 kg N ha^{-1} to the following crop. Calculation by Moncrief (Personal Communication) showed that lupines contribution is an equivalent of 60 kg ha^{-1}. This lupine N contribution was converted into an equivalent amount of crop residue assuming a C:N ratio of 15. This procedure assumes that lupine N availability was the same as the N availability from crop residues. In CERES-maize, mineralization of organic nitrogen from crop residue is calculated using the mineralization and immobilization routines given in the PAPRAN model (Seligman and van Keulen, 1981). Crop residues are divided into three groups of material: carbohydrate, cellulose and lignin with the corresponding decomposition rate of 0.05, 0.0045 and 0.00095 d^{-1}, respectively. The decomposition rates were taken from Vigil et al. (1991). Mineralized nitrogen for each group of materials is calculated daily and summed together to get the maximum nitrogen that can possibly be mineralized from crop residues on a given day. This amount is then modified to account for limiting conditions due to soil temperature, soil water content and carbon-nitrogen ratio to calculate the net amount of nitrogen mineralized from crop residues on any given day.

RESULTS AND DISCUSSION

Field Results

Detailed results of the field experiments are given in Sexton (1993) and only the results related to the model validation are presented here. Although there were some differences in applied irrigation amounts, irrigation did not significantly affect corn yield for a given fertilizer treatment both during 1991 and 1992. Variable irrigation rate (schedule #2) based on crop growth stage produced slightly higher yields and lower nitrate leaching. Corn grain yields responded up to the 184 kg N ha^{-1} of N application in both years. The cooler growing season of 1992 reduced corn grain yields by up to 40% compared to 1991. Nitrate leaching under corn increased significantly at N application rates greater than those required to achieve the maximum grain yield.

Model Validation

The CERES-Maize model was validated for corn yield, N-uptake (above ground), and N-leaching. A comparison of the simulated and measured silking and physiological maturity dates are shown in Table 3-4. Since the differences between simulated and measured silking and physiological maturity dates (Table 3-4) are small (2 and 6 days, respectively), this suggests that a proper set of genetic parameters (P1) and (P5) have been assigned for the simulation.

An example of the output from the CERES-Maize model on percolation and N-leaching as a function of precipitation and irrigation is shown in Figure 3-3. As is evident from these data, N leaching is mostly due to rainfall events either alone or in combination with an irrigation event. For example, the peak N leaching occurs on day of the year (DOY) 180 (June 30). This is also the date when percolation losses are near maximum. This date corresponds to a day with high precipitation occurring shortly after an irrigation. Nitrogen leaching is maximum on this date because of combination of a higher percolation amount and a higher concentration of nitrate in the last soil layer.

An example of the comparisons between measured and simulated corn yield, N-uptake and N-leaching for 1991 and 1992 under the fixed irrigation schedule (schedule #1) is shown in Figures 3-4 and 3-5, respectively. The observed and simulated values are close to each other for the check treatment. However these differences increased with an increase in N-application rate. The predicted corn yields are about 3 Mg ha^{-1} higher than the measured values at an N application rate of 284 kg N ha^{-1} in 1991. This difference between measured and simulated values might be because the CERES-Maize model does not account for the other crop growth-limiting factors such as insect and disease infestation. Since the crop yield is also slightly higher for other N-input levels, it is possible that these higher yield at the high N-input are magnified due to a lack of factors accounting for disease and insect infestation.

Statistical parameters describing the comparison between measured and predicted values of corn yield, N-uptake and N-leaching for both 1991 and 1992 over fixed and variable irrigation schedules are given in Table 3-5. The differences between the predicted and the measured corn yields and N uptake were not significant at the 5 percent probability level using a paired t-test (test of intercept =0, and slope=1). However, the simulated N-leaching were significantly different from the measured values at the 5 percent probability level.

Sensitivity Analysis

Crop and soil parameters: Sensitivity analysis of the CERES-Maize was conducted to test the sensitivity of predicted crop yield and nitrate leaching to initial soil inorganic N level, corn relative maturity and SWCON. The sensitivity tests were performed for the fixed rate irrigation schedule and the 284 kg N ha^{-1} N treatment used in the 1991 experiment of Sexton (1993). Initial N values included both NH_4 and NO_3 levels in the soil. The relative maturity effects were simulated by using different relative maturity hybrids in the simulations. The genetic parameters for these hybrids are included as options in the model. SWCON is a fraction of soil water that leaches in one day and is an equivalent of the hydraulic conductivity of the soil profile.

Changes in corn yield and N leaching due to a variation in soil initial N value, relative maturity hybrids and SWCON are shown in Figure 3-6. Both simulated corn yield and nitrate leaching increase with an increase in initial soil N (Figure 3-6a), however, the increase in N-leaching is much greater than the increase in crop yield. Simulated corn yield is also sensitive to the selection of corn hybrid (Figure 3-6b). Maximum yield is obtained for the Pioneer 3921, a hybrid selected for this simulation study. The simulated N-leaching from CERES-Maize model is not affected by the selection of a corn hybrid. Simulated yield and N-leaching are both sensitive to the value of SWCON (Figure 3-6c). Corn yield decreases whereas N-leaching increases with an increase in the value of SWCON. This decrease in yield is due to a lack of N availability for plant growth because of excessive N loss as a result of rapid drainage.

Irrigation Management: Since the two irrigation schedules used by Sexton (1993) were nearly similar, both in amount and timing of irrigation, measured corn yield and N leaching were nearly similar for both irrigation schedules in each year. Thus, based on Sexton's data it was not apparent if irrigation management has any significant effect on corn yield and N-leaching in outwash soils of Minnesota. To test the effect of irrigation management on corn yield and N-leaching, simulation runs were made at various irrigation trigger levels. Irrigation trigger refers to the percent of the extractable water in the top 0.6 m of the soil profile allowed to remain in the soil profile before irrigation is triggered. For example, 40% irrigation trigger means that irrigation is applied when water amount in the top 0.6 m soil reaches 40% of the extractable water. In other words, a minimum of 40% of the extractable water is always present in the soil for the 40% irrigation trigger.

An example of the variation in the simulated corn yield, irrigation amount, N-leaching, and water and N stress factors at various irrigation trigger levels for fertilizer treatment #3 (184 kg ha^{-1}) during 1991 is shown in Figure 3-7. At irrigation trigger level of 30% and above, the crop yield is not influenced by trigger deficit. The amount of irrigation applied and N leaching increases with an increase in irrigation trigger level. Although there is no water stress at irrigation trigger of 30% and above, there is a slight increase in N stress for irrigation trigger level of greater than 30%. A slight dip in N leaching at 50% irrigation trigger is a result of a unique combination of timing of irrigation and precipitation. This dip in N leaching will not necessarily occur in all years and especially at this irrigation trigger level. In general at higher irrigation trigger levels, irrigation was applied more frequently but at a smaller amounts (Figure 3-8). Comparison of percolation for various irrigation strategies shows that frequent irrigations even in smaller amounts increase the probability of percolation especially if there is small rainfall right after an irrigation event (Figure 3-9). Conversely, higher amounts of infrequent irrigation at lower irrigation triggers (Figure 3-8) lead to lower seasonal probability of percolation and thus lower N leaching (Figure 3-9) even if precipitation occurs right after irrigation. This is mainly because during simulation the soils are always brought to field capacity and there is no unfilled pore space available that will capture rain if it occurs right after irrigation. This analysis suggests that leaving some unfilled porespace after each irrigation will help capture rain and thus minimize N leaching. This is consistent with the observation of Watts and Martin (1981) who showed that nitrate leaching loss increase due to either rain or excess irrigation for a sandy soil in Nebraska. Figure 3-7 shows that lower irrigation triggers also result in less application of irrigation water and thus some savings in water for Minnesota climatic conditions.

To test if this trend in crop yield and N leaching applies to all types of fertilizer treatments, simulation were also run on three other fertilizer treatments (annual application of 20, 101, and 284 kg N ha^{-1}) used by Sexton (1993) during 1991. Irrigation triggers considered in this analysis were 40, 60 and 80% of the soil extractable water. As expected, simulated crop yields are nearly the same for all three irrigation triggers, however, there is a substantial difference in N leaching between the three irrigation triggers (Figure 3-10). In this sensitivity analysis, nitrogen leaching is minimal at an irrigation trigger level of 60%, however, this is specific to weather conditions of 1991. In other words, the rate of increase of N leaching with an increase in N rate is higher for 40% and 80% irrigation triggers compared to 60%. In terms of economics, the data show that optimum yield occurs near the N input of 180 kg N ha^{-1}. However, in terms of N leaching, the best N application rate where there is a minimal increase with each additional unit of N application corresponds to N application of 100 kg N ha^{-1}.

<u>Climate:</u> Since weather varies over time, best management practices delineated based on a simulation of one year will not necessarily be the best management practices for a given soil in a given area. To truly identify the best management practice, simulations must be run over many years with different weather conditions. To demonstrate the effect of year to year weather variability on corn yield and N leaching, simulations were run for thirty one years (1963-1993). Maximum and minimum air temperatures and precipitation data were taken from weather records of the Wadena weather station (Station ID: 218579, National Weather Service), Wadena county, MN (State Climatology Office, MN). The Wadena weather station is located about 12 km west of the Staple Irrigation Center.. Since solar radiation data for the Wadena weather station were not available, these records were obtained for a site in St. Paul, MN (Baker D. G. 1994. Soil, Water and Climate Department, University of Minnesota, St. Paul, MN. Personal Communication). By using the solar radiation data from St. Paul, MN in our simulation studies, we made an implicit assumption that solar radiation at St. Paul, MN and Staples, MN are similar. Considering that St. Paul, MN and Staples, MN are about 250 km apart and solar radiation is nearly constant over a wide area, the above assumption is reasonable and should not cause any major error in our simulation results.

Three irrigation triggers of 40, 60 and 80% of the extractable water were used for these simulations. Other inputs on soil and crop properties used were the same as previously discussed in validation of the model. Yearly simulated results of corn yield and N-leaching were converted to a cumulative probability basis. Briefly, the procedure involved arranging the yield and N-leaching data in ascending order and then calculating the cumulative probability as follows:

$$\text{Cumulative Probability} = \frac{i}{n + 1} \qquad [1]$$

where i is the i th year after the data has been arranged in ascending order and n is the total number of years for which the data is available. In this study, n is equal to 31. Cumulative probability for crop yield and N leaching were separately calculated by arranging each data set in its own ascending order. Simulations were run for four N application rate treatments (21, 101, 184 and 284 kg N ha^{-1}).

Cumulative probabilities of corn yield and N-leaching for a combination of four N rates and three irrigation triggers are plotted in Figures 3-11 and 3-12. Since we had arranged the yield and N leaching in ascending order for calculating cumulative probability, cumulative probability increases with an increase in yield and N leaching. The cumulative probability curves are not smooth because the data covers only a short period of 31 years.

Fifty percent cumulative probability in Figures 3-11 and 3-12 refers to 5 out of 10 years which is similar to a median year. Relationship between yield and N leaching with several independent variables (data not showed) showed that yield increased with an increase in growing degree days (r^2=0.75) and N leaching increased with an increase in rainfall amounts (r^2=0.52). This suggests that higher corn yield corresponds to warmer years, whereas, higher N leaching corresponds to wet years. For demonstration of our concepts and procedures, we choose 75% and 25% as upper and lower probabilities levels. Cumulative probability of 75% for yield refers to a warmer year and 25% probability refers to a cooler year. Similarly, cumulative probability of 75% for N leaching refers to a wet year and cumulative probability of 25% refers to a dry year.

Data in Figures 3-11 and 3-12 show that for a given irrigation trigger, crop yield and N-leaching increase with an increase in fertilizer addition. The differences in crop yield between check (21 kg N ha^{-1}) and the other three N rates are much higher than the differences among the three N rates. Conversely, N- leaching for the check and the first two N rates is nearly similar. However, the differences in N-leaching between the first three N rates (21, 101, and 184 kg N ha^{-1}) and the fourth (284 kg N ha^{-1}) are much greater.

For any given N rate, the differences in crop yield between the three irrigation triggers (40, 60 and 80%) are small. Conversely, for any given N rate, the differences in N leaching between the three irrigation triggers (40, 60 and 80%) are large. In general, N-leaching increases with an increase in irrigation trigger level, but the rate of increase in N-leaching is much greater for the higher fertilizer application rates.

Soil Specific Risk Characterization

The validated CERES-Maize model provides a tool to characterize the risk potential of various soils to nitrate leaching. Various procedures can be used to develop the risk characterization schemes. The simplest scheme could be the characterization of soil based on the absolute amount of N leached past the root zone. The other scheme could be based on the magnitude of N-leaching relative to the amount applied. The former approach is used in this manuscript to demonstrate the development of a risk index to characterize the risk of nitrate leaching in different soils under various management scenarios. It is assumed that each 20 kg N ha^{-1} leached represents a risk category. This is slightly different than the risk indices suggested by Khakural and Robert (1993) in which each risk category is associated with a variable rate of N leaching. Various risk categories or risk indices used in this study are follows:

Risk Category	N-leached (kg N ha^{-1})
I	0-20
II	20-40
III	40-60
IV	60-80
V	80-100
etc.	

Simulation results in Figure 3-12 show that at 50% cumulative probability (an average year), Verndale sandy loam when managed at 40% irrigation trigger level, represent the risk categories of I, I, II and III for fertilizer application rates of 21, 101, 184 and 284 kg N ha^{-1}, respectively. If a different irrigation trigger level is selected or the precipitation amount and the pattern of precipitation is different than that of the average year then the risk index of the soil changes. For example, the risk indices of Verndale sandy loam for an N application of 284 kg N ha^{-1} at irrigation triggers of 40, 60, and 80% are III, III, and IV, respectively. Similarly, the risk indices of Verndale sandy loam for an N application of 284 kg N ha^{-1} and at an irrigation trigger of 40% are III, II and III when the climate of the location varies from an average year (50% cumulative probability) to dry (25% cumulative probability) and wet (75% cumulative probability) year, respectively.

Application of Risk Indices

An application of the above risk characterization procedure is demonstrated by characterizing the potential of nitrate leaching from major soils of Wadena county in Minnesota. Table 3-6 lists six major soils in Wadena county based on their area. For each of these soils, soil characteristics were taken from Wadena County, MN Soil Survey (SCS, 1991) or from the Soil Survey Characterization Laboratory at the University of Minnesota. Simulations were run for three irrigation trigger levels (40, 60, 80%) and four N application rates (21, 101, 184, and 284 kg N ha^{-1}) over 31 one years (1963-1993). Cumulative probability curves were developed for corn yield and N leaching for 72 combinations of soils, irrigation trigger levels and fertilizer application rates. N leaching at three probability levels (25, 50 and 75%) were read from the cumulative probability curves.

Using the criteria of 20 kg N ha^{-1} leaching for each category, soils were characterized for their risk to nitrate leaching. The categories are mapped in a section of soil around the Staple Irrigation Center in Wadena county (Figures 3-13 through 3-15). These figures show the effect of soil type, fertilizer application rate, irrigation trigger levels and climate on risk characterization of soils to nitrate leaching. For example, the effect of fertilizer application rate on risk characterization of soils to nitrate leaching for an irrigation trigger of 60% and at a cumulative probability of 50% are shown in Figure 3-13. Changes in risk indices of soils to nitrate leaching as a function of various irrigation trigger levels at a N application rate of 284 kg ha^{-1} and at a cumulative probability of 50% are shown in Figure 3-14. Effect of yearly weather variability on changes in risk indices of soils to nitrate leaching is shown in Figure 3-15 for an irrigation trigger of 60% and at a N application rate of 284 kg ha^{-1}. Non-colored spaces in Figures 3-13 through 3-15 are high organic matter soils like Seelyeville muck, Rifle mucky peat, and Markey muck. Since hydraulic characterization for these soils is not available, simulations were not run for these soils.

In general, Blower sandy loam has the least risk whereas Menahga loamy sand has the most risk in terms of N leaching among six major soils of Wadena county. This is because Blower sandy loam has a higher water holding capacity as well as lower drainage compared to Menahga loamy sand. Water holding capacity in the 1.5 m profile of Blower sandy loam was 33.2 cm compared to 12.5 cm for Menahga loamy sand. SWCON (soil drainage parameter) was 0.5 for Blower sandy loam compared to 0.8 for Menahga loamy sand. At any probability level, corn yields were nearly the same for a given N rate and irrigation trigger. This is expected considering water was applied as necessary and climate input for all these soils was the same. The response of crop yield and N leaching (data not shown) of each unit of N addition was much greater in soils with low water holding capacity and rapid drainage (Menahga loamy sand) compared to soils with larger water holding capacity and lower drainage rate (Blower sandy loam).

Figures 3-13 through 3-15 demonstrate how the CERES-Maize model can be linked to the soil survey data to characterize the risk potential of various soils to nitrate leaching. Considering that most of the soil survey information is being computerized nation wide, this type of linkage between the Crop-Environment-

Resource-Synthesis (CERES) Model and soil survey data base can be a valuable tool in assessing and prescribing the best management practices by soil, field or farm type.

CONCLUSIONS

Simulated corn yield, N-uptake and N-leaching from the CERES-Maize model were within range of the measured values for Verndale sandy loam over two years. Sensitivity analysis showed that infrequent irrigations but in larger amounts (allowing the soil to deplete to higher deficits before irrigation) results in less N leaching without significantly affecting the corn yield. Any trigger irrigation above a value of 30% of the extractable water remaining in soil resulted in nearly similar corn yields.

Higher application of commercial nitrogen fertilizer leads to higher N leaching. Since rate of yield increase is small and the rate of N leaching is large with additional N input, the optimum N application treatment in terms of economics is near an application rate of 180 N ha^{-1}. However in terms of N leaching to groundwater, the best N application rate corresponds to N application of 100 kg N ha^{-1}. Both of these rates are much smaller than the recommended rate of 245 kg ha^{-1}.

Most N leaching in Central Sands of Minnesota are controlled by rainfall events either alone or in combination with an irrigation. Even with the most efficient irrigation schedule, N leaching in Central Sands of Minnesota occurs if it rains right after an irrigation. Therefore, rainfall relative to the timing of irrigation is a major determinant in controlling N leaching. In general, wet years lead to higher N leaching. To minimize the probability of N leaching due to rainfall, soils should be irrigated to less than the field capacity water content so that there is some unfilled porespace that will capture rain should it occur right after irrigation.

A procedure is presented to characterize the risk potential of soils to N leaching for nitrogen and irrigation management schemes. Using the simulated cumulative probability curves for corn yield and N leaching, examples are given that show a change in risk potential of a soil to N leaching with changes in climate. Examples are given to demonstrate how the predictions of nitrate leaching from the CERES-Maize model can be linked with the soil survey data base to characterize the risk potential of various soils to nitrate leaching in a given field. This linkage can be a valuable tool in assessing and prescribing best irrigation and nitrogen management practices for outwash soil of the North Central region in a site specific farming concept.

REFERENCES

Ayisi, K. K. 1991. Biological nitrogen fixation in white lupin. M. S. Thesis, Univ. of Minn., St. Paul, MN.

Cooter, E. J. 1990. The impact of climate change on continuous corn production in the southern U.S. Climate Change, 16:53-82.

Council for Agriculture Sciences and Technology (CAST). 1985. Agriculture and water quality. Rep. No. 103. Council for Agricultural Sciences and Technology, Ames, IA.

Hallberg, G. R., R. D. Libra, E. A. Bettis and B. E. Hoyer. 1984. Hydrogeologic and water quality investigations in Big Spring Basin, Clayton county, Iowa: 1983 water year. Open-file Rep. No. 84-4. Iowa Geological survey.

Hodges, T., D. M. Botner, C. M. Sakamoto, and J. Hays-Haug. 1987. Using the CERES-Maize model to estimate production for the US Corn Belt. Agric. For. Meteorol., 40, 293-303.

Jones, C. A., and J. R. Kiniry (Eds.). 1986. The CERES-Maize: A simulation Model of Maize Growth and Development. Texas A & M University Press. College Station, Texas.

Khakural, B. R. and P. C. Robert. 1993. Soil nitrate leaching potentials indices: using a simulation model as a screening system. J. Environ. Qual. 22:839-845.

Klaseus, T. G., G. C. Buzicky, and E. C. Schneider. 1988. Pesticides and groundwater: Survey of selected Minnesota wells. Report for the legislative Commission on Minnesota Resources. Minnesota Dept. of Health and Minnesota Dept. of Agriculture.

Myette, C. F. 1984. Groundwater quality appraisal of sand plain aquifers in Hubbard, Morrison, Otter tail, and Wadena counties, Minnesota. U.S. Geological survey. Water-Resources Investigations Report 84-4080. St. Paul, MN.

Nielsen, E. G. and L. K. Lee. 1987. The magnitude and costs of groundwater contamination from agricultural chemicals: A national perspective. Agricultural Economic Rep. No. 576, U. S. Dept. of Agriculture.

Pang, X. P., S. C. Gupta, J. F. Moncrief, and D. G. Baker. 1992. Probabilities of percolation losses in Minnesota outwash soils. Presented on The 84th Annual Meeting of ASA, CSSA, SSSA. Minneapolis, MN, Nov.1-6, 1992.

Ritchie, J. T., and J. Crum. 1989. Converting soil survey characterization data into IBSNAT crop model input. In: J. Bouma and A. K. Bregt (Eds.): Land qualities in space and time. Wageningen, the Netherlands, pp 155-167.

Sexton, B. T. 1993. Influence of nitrogen and irrigation management on corn and potato response and nitrate leaching. M. S. Thesis, University of Minnesota, St. Paul, MN.

Seligman, N. G. and H. van Keulen. 1981. PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen. pp 192-221. In M. J. Frissel and J. A. van Veen (Eds.), Simulation of Nitrogen Behavior of Soil-Plant Systems. PUDOC, Wageningen, The Netherlands.

Soil Survey of Wadena County, MN. 1991. SCS-USDA.

Vigil, M. F., D. E. Kissel, and S. J. Smith. 1991. Field crop recovery and modeling of nitrogen mineralized from labeled sorghum residues. Soil Sci. Soc. Am. J. 55: 1031-1037.

Watts, D. G., and D. L. Martin. 1981. Effects of water and nitrogen management on nitrate leaching loss from sands. Trans. Am. Soc. Agril. Eng. 24: 911-916.

Wright, J. and F. Bergsrud. 1986. Irrigation Scheduling checkbook method. AG- FO-1322. Minn. Ext. Serv., Univ. Minn., St. Paul, MN.

Wu, Y., C. M. Sadamoto, and D. M. Botner. 1989. On the application of the CERES-Maize model to the north China plain. Agric. For. Meteorol.,49,9-22.

Table 3-1. Date of sowing, planting density, irrigation amount, crop growth parameters, and crop yield in field trials at the Staples Irrigation Center (Sexton, 1993).

Year	Sowing date mon.-day	Planting density plant ha^{-1}	Irrigation mm	50% Silking dare ---- mon.-day	Harvest date ------	Grain-yield -----(Mg ha^{-1})	Biomass ----------
1991	5-8	79000	182	7-14	9-18	7.18	17.76
1992	5-5	74100	154	8-4	10-14	6.06	12.52

Table 3-2. The date and amount of commercial fertilizer application (Sexton, 1993).

Fert. treat.	1991 Date mon.-day	1991 Amount ------ kg ha^{-1}	1991 Total ------	1992 Date mon.-day	1992 Amount ----- kg ha^{-1}	1992 Total -------------
#1	5-8	20	20	5-5	30	30
#2	5-8	20		5-5	30	
	5-29	40		6-8	31	
	6-13	40	100	6-30	31	92
#3	5-8	20		5-5	30	
	5-29	82		6-8	76	
	6-13	82	184	6-30	76	182
#4	5-8	20		5-5	30	
	5-29	132		6-8	122	
	6-13	132	284	6-30	122	274

Table 3-3. Genetic data for hybrid Pioneer 3921 and soil data for Staples Irrigation Center, as used in the validation of CERES Maize.

Genetic data†

Hybrid	P1 d °C	P2 h^{-1}	P5 d °C	G2 kernels $plant^{-1}$	G3 mg $kernel^{-1}$ d^{-1}
Pioneer 3921	140.0	0.0	690.0	825.0	10.0

Soil data‡

Horizon	Depth cm	Density Mg m^{-3}	LL cm cm^{-3}	DUL cm cm^{-3}	SAT cm cm^{-3}	OM %	Total N mg kg^{-1}	pH
Ap	0-25	1.57	.070	.230	.407	1.30	1.9	6.9
Bt	25-40	1.78	.100	.270	.328	0.70	2.1	6.6
Bc	40-53	1.57	.070	.230	.407	0.50	2.1	6.6
C	53-83	1.57	.070	.150	.396	0.30	2.1	6.5

† P1: thermal time from seed emergence to the end of juvenile;
P2: photoperiod sensitivity coefficient;
P5: thermal time from silking to physiological maturity;
G2: potential kernel number; G3: potential kernel growth rate;

‡ Density: bulk density; LL: lower limit of available soil water;
DUL: drained upper limit of available soil water;
SAT: saturated limit of available soil water; OM: organic matter content;
Total N: total initial soil nitrogen content, $NO_3 + NH_4$.
Albedo = 0.20. Run off curve number =62
Soil drainage class: well drained

Table 3-4. A comparison of simulated and measured dates for silking and black layer formation.

Growth Stage	1991 date†	1992 date†
75% silking	July 14/July 12	Aug 4/Aug 5
Physiol.maturity (black layer)	Aug 30/Sept 4	Sept 30/Sept 24

† measured/simulated

Table 3-5. Correlation and regression parameters describing the closeness of fit between simulated and measured corn yield, NO_3 leaching, and total N uptake.

	a	b	R^2
Yield	-0.64	1.29	0.90
NO_3 leaching	2.73	0.50	0.50
N uptake	15.0	1.18	0.72

Y (Simulated) = a + b * X (measured)

Table 3-6. Major soils and their physical characteristics of Wadena county, MN.

Soil name	Map symbol†	Area ha	Soil texture	WHC‡ cm	SWCON day^{-1}
Dorset	406 A,B	1721	Sandy loam	16	0.6
Oylen	1975	2991	Sandy loam	15	0.5
Nymore	207A,B	6296	Loamy sand	11	0.8
Verndale	567A,B	11095	Loamy sand	12	0.6
Blower	720B	12014	Sandy loam	23	0.5
Menahga	1970B	18751	Loamy sand	9	0.8

† Map symbol used in Soil Survey of Wadena County, MN (1991) are also shown in Figures 13 through 15.
‡ WHC = Water Holding Capacity of top 1.5 meter soil.

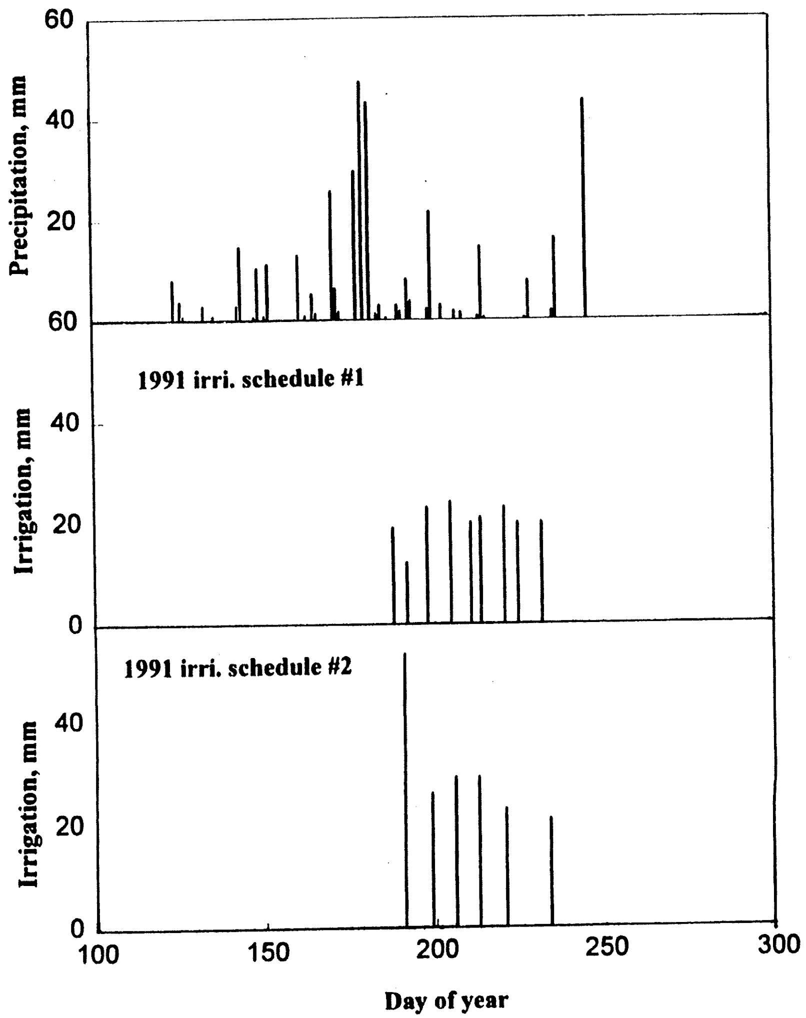

Figure 3-1. Precipitation and irrigation amounts as a function of day of the year during 1991 in the field trial of Sexton (1993) at Staples, MN.

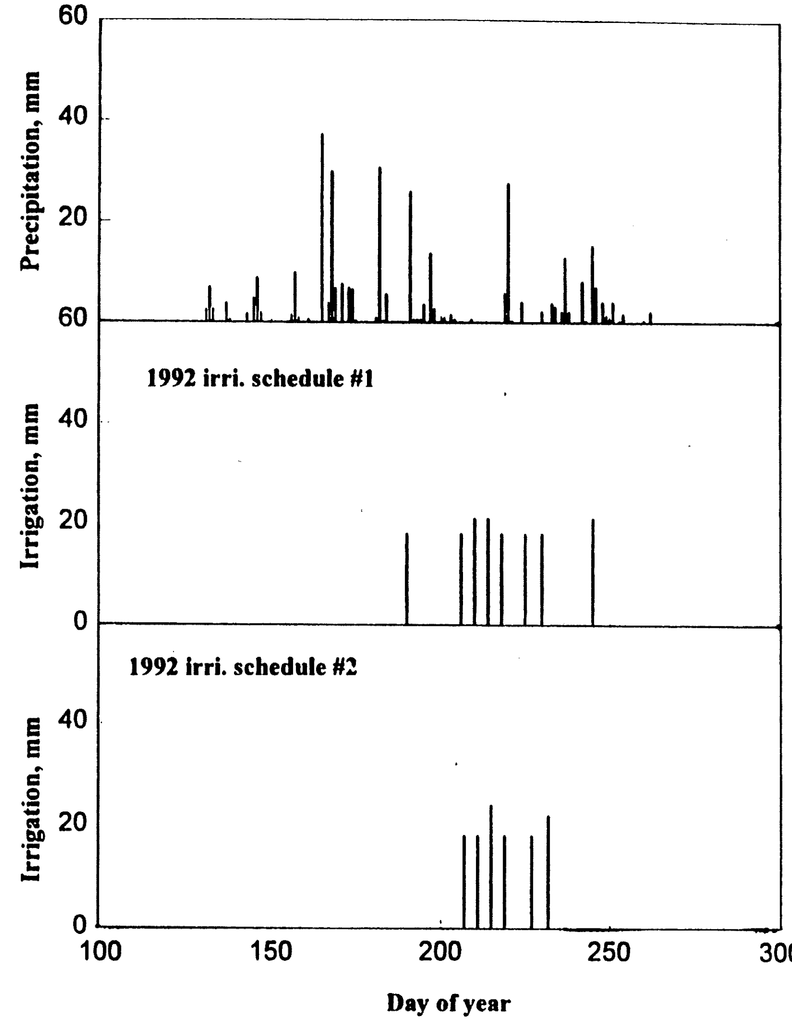

Figure 3-2. Precipitation and irrigation amounts as a function of day of the year during 1992 in the field trial of Sexton (1993) at Staples, MN.

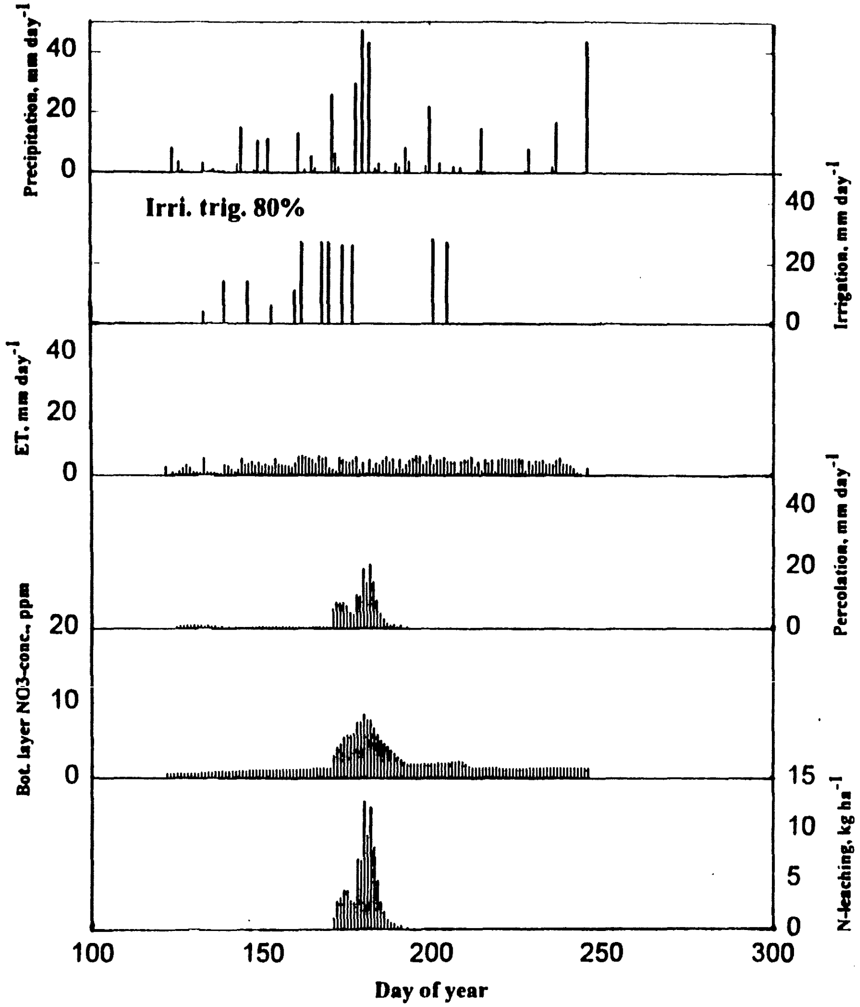

Figure 3-3. An example of the simulation outputs from the CERES-Maize model of daily evapotranspiration, percolation, last soil layer N concentration and N leaching as influenced by precipitation and irrigation at Staples, MN.

Simulations are for a fixed irrigation schedule (fixed at 80% of the extractable water remaining in soil) during 1991 with fertilizer addition of 184 kg N ha^{-1}.

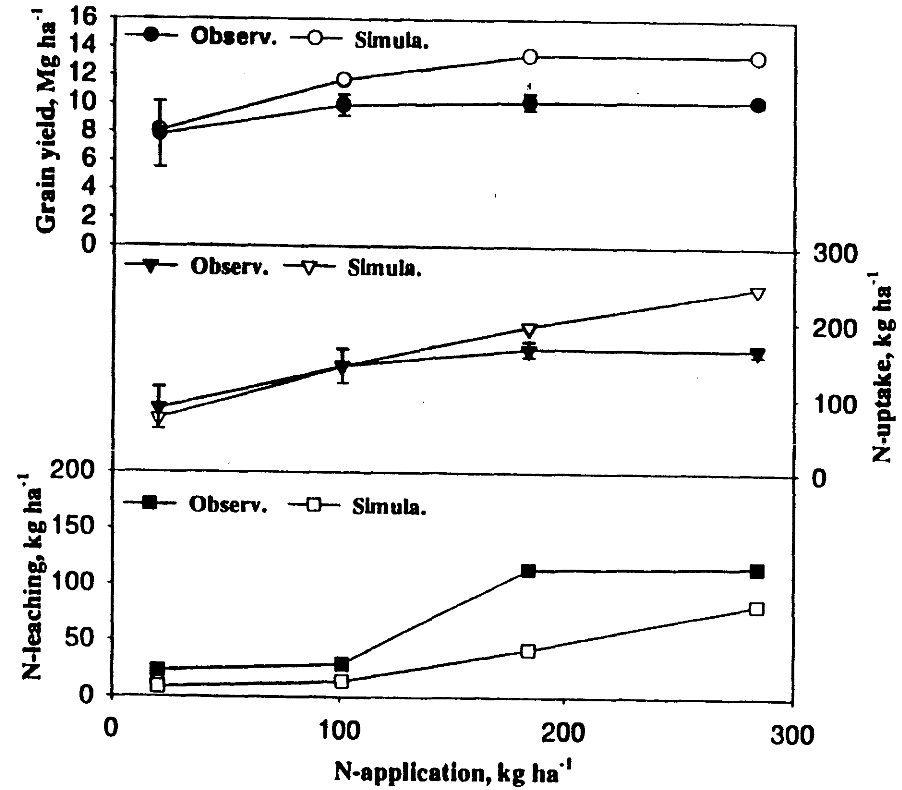

Figure 3-4. Comparison of measured and predicted corn yield, N-uptake and N-leaching in Verndale sandy loam as a function of N-application for a fixed irrigation schedule during 1991.

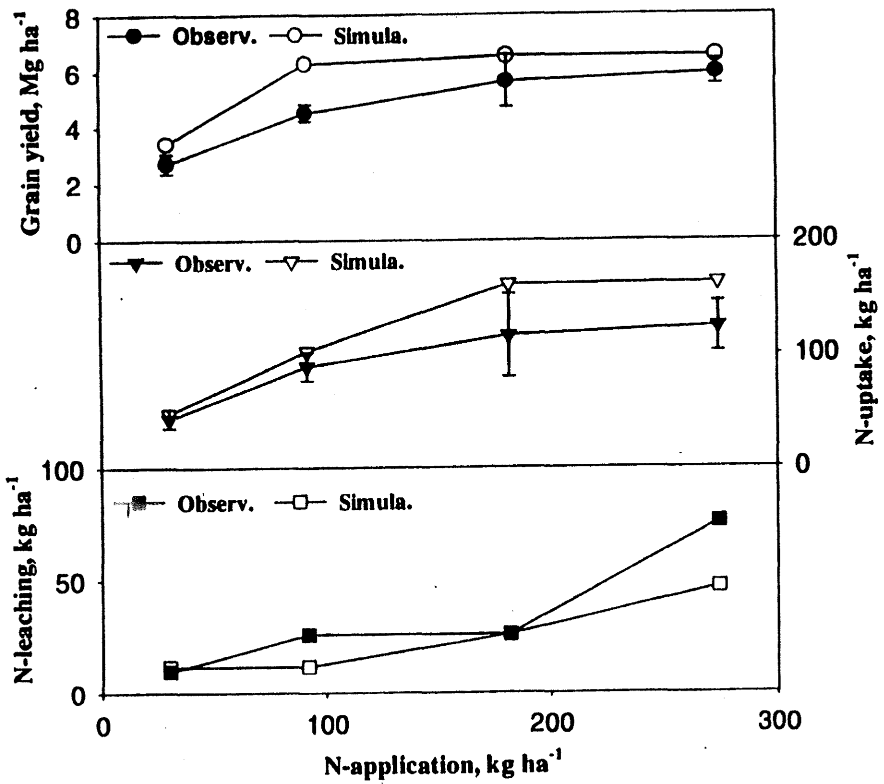

Figure 3-5. Comparison of measured and predicted corn yield, N-uptake and N-leaching in Verndale sandy loam as a function of N-application for a fixed irrigation schedule during 1992.

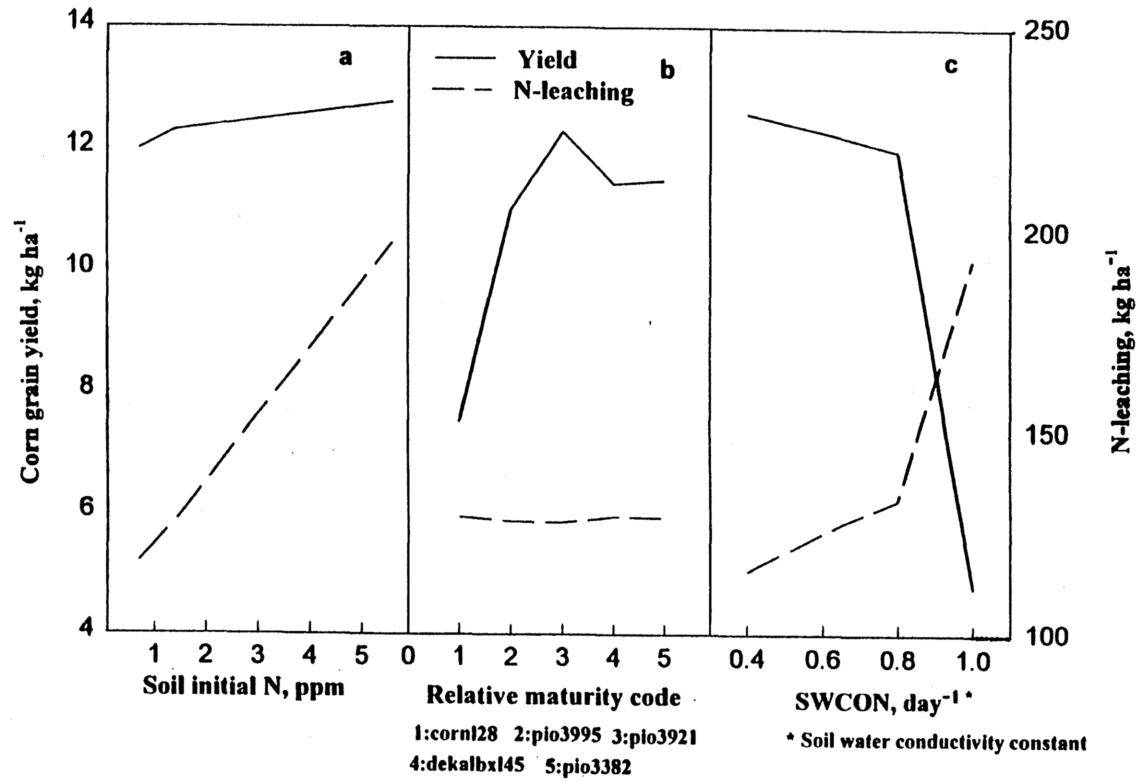

Figure 3-6. Sensitivity analysis of predicted corn yield and N-leaching as a function of initial inorganic soil N, different relative maturity hybrid, and SWCON (soil drainage factor). Simulations are for fixed irrigation schedule during 1991 with fertilizer addition of 284 kg N/ha at Staples, MN.

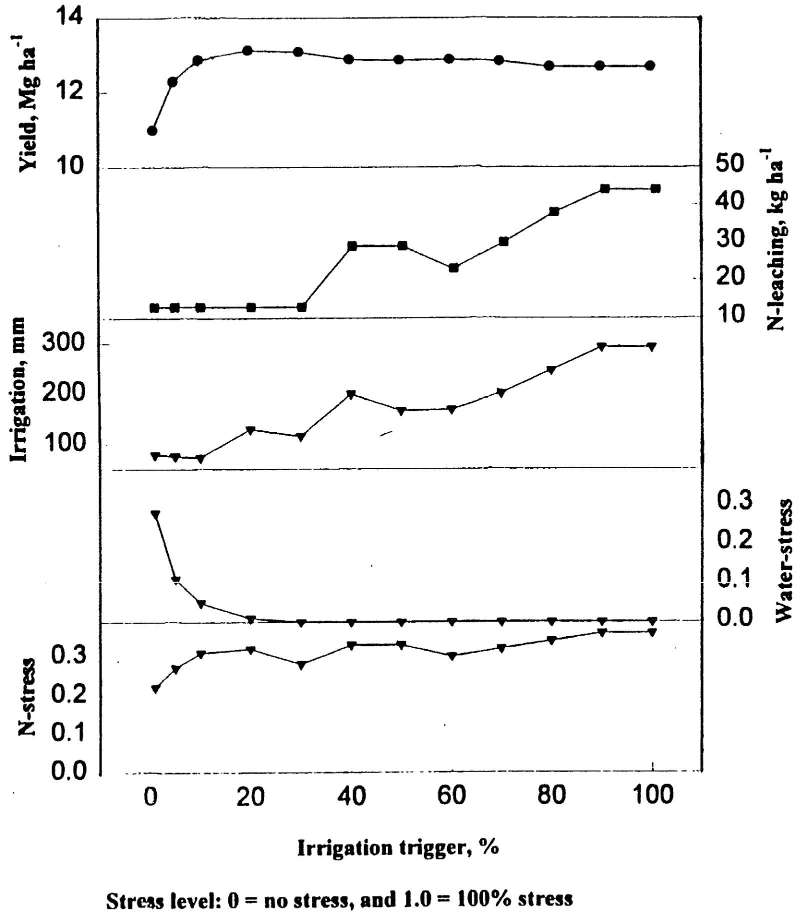

Figure 3-7. Effect of various irrigation triggers (percent of extractable water remaining in soil before irrigation) on simulated corn yield, N leaching amount, and water and N stress at fertilizer application of 184 kg N/ha during 1991 at Staples, MN.

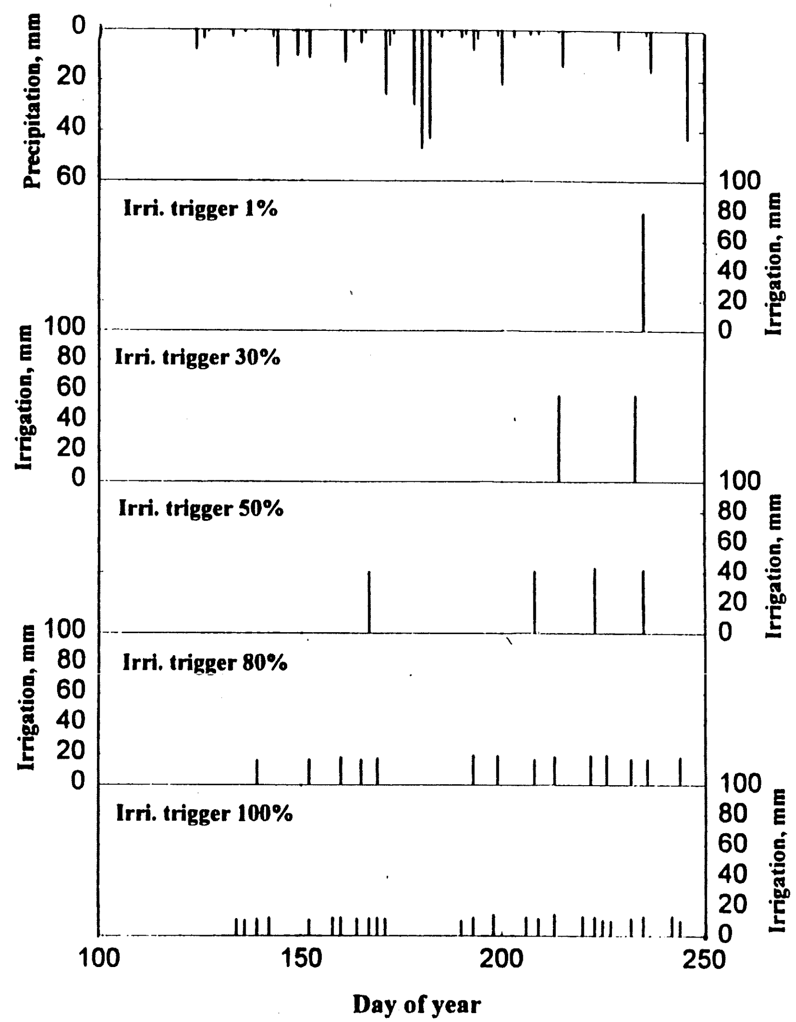

Figure 3-8. Variation in irrigation application for various irrigaiton triggers (percent of extractable water remaining in soil before irrigation) during 1991 at Staples, MN as simulated by CERES-Maize.

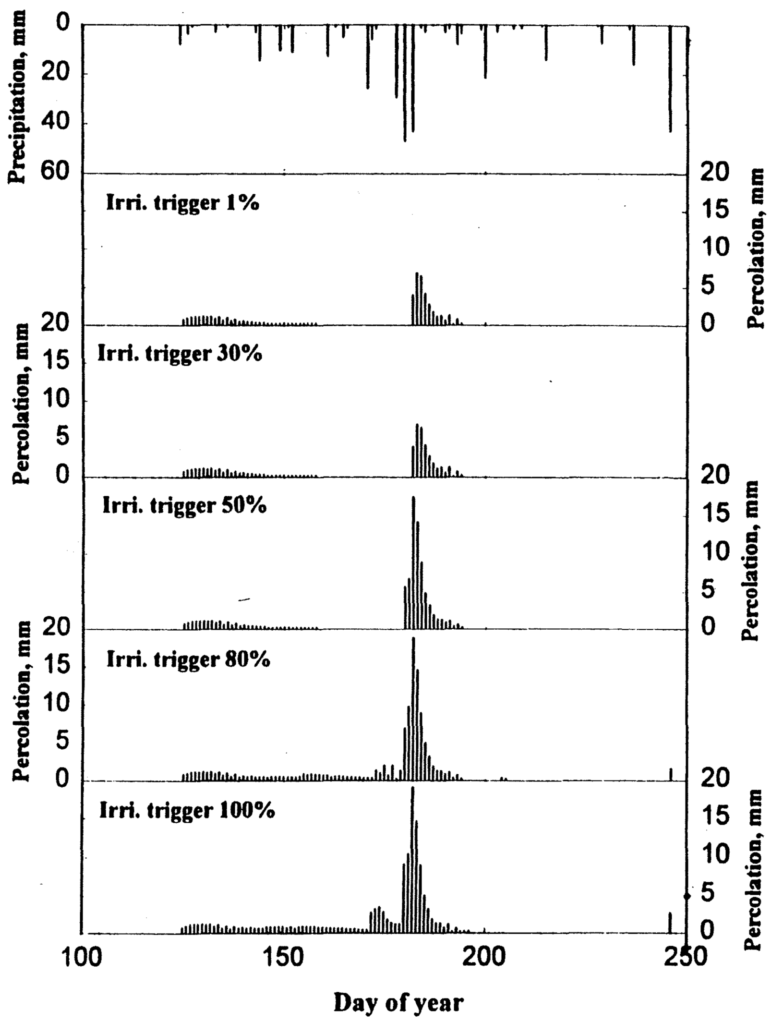

Figure 3-9. Variation in percolation for various irrigaiton triggers (percent of extractable water remaining in soil before irrigation) during 1991 at Staples, MN as simulated by CERES-Maize.

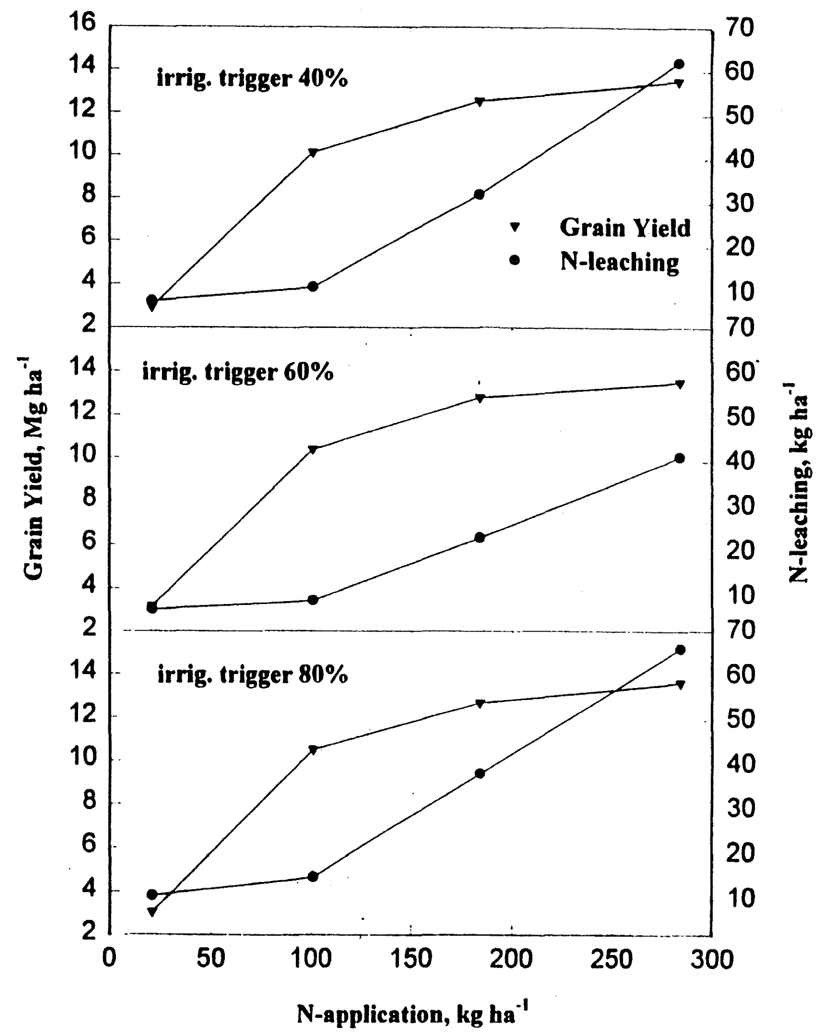

Figure 3-10. Simulated corn yield and N-leaching as a function of N application rate at irrigation triggers of 40, 60, and 80% during 1991 at Staples, MN.

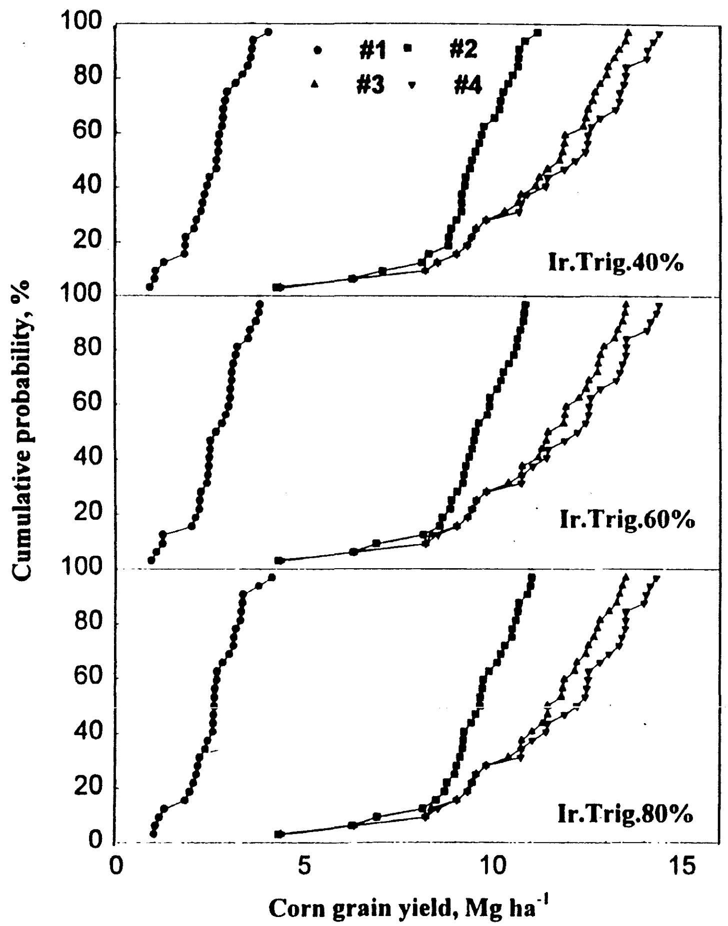

Figure 3-11. Cumulative probabilities of corn grain yield as a fuction of four fertilizer application rates and three irrigation triggers (40, 60 and 80%) at Staples, MN. Fertilizer treatments #1, #2, #3 and #4 correspond to N application of 21, 101, 184 and 284 kg N/ha. Cumulative probability of 50% refers to a median year weather and cumulative probabilities of 75% and 25% refer to a warm and a cold year weather, respectively.

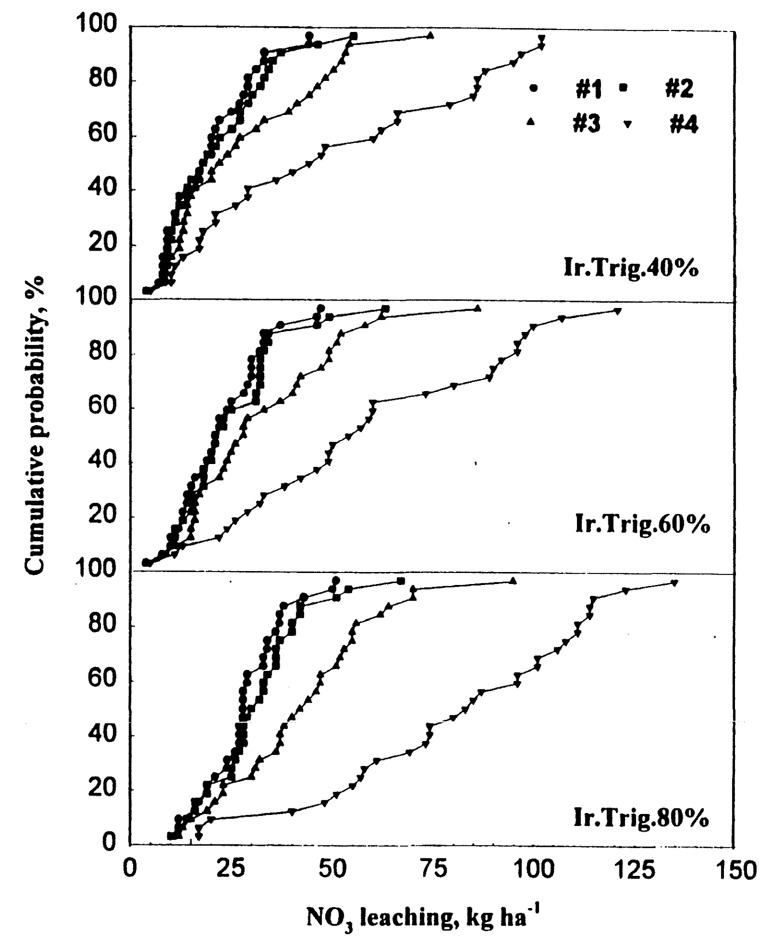

Figure 3-12. Cumulative probabilities of nitrate leaching as a fuction of four fertilizer application rates and three irrigation triggers (40, 60 and 80%) at Staples, MN. Fertilizer treatments #1, #2, #3 and #4 correspond to N application of 21, 101, 184 and 284 kg N/ha. Cumulative probability of 50% refers to a median year weather and cumulative probabilities of 75% and 25% refer to a wet and a dry year weather, respectively.

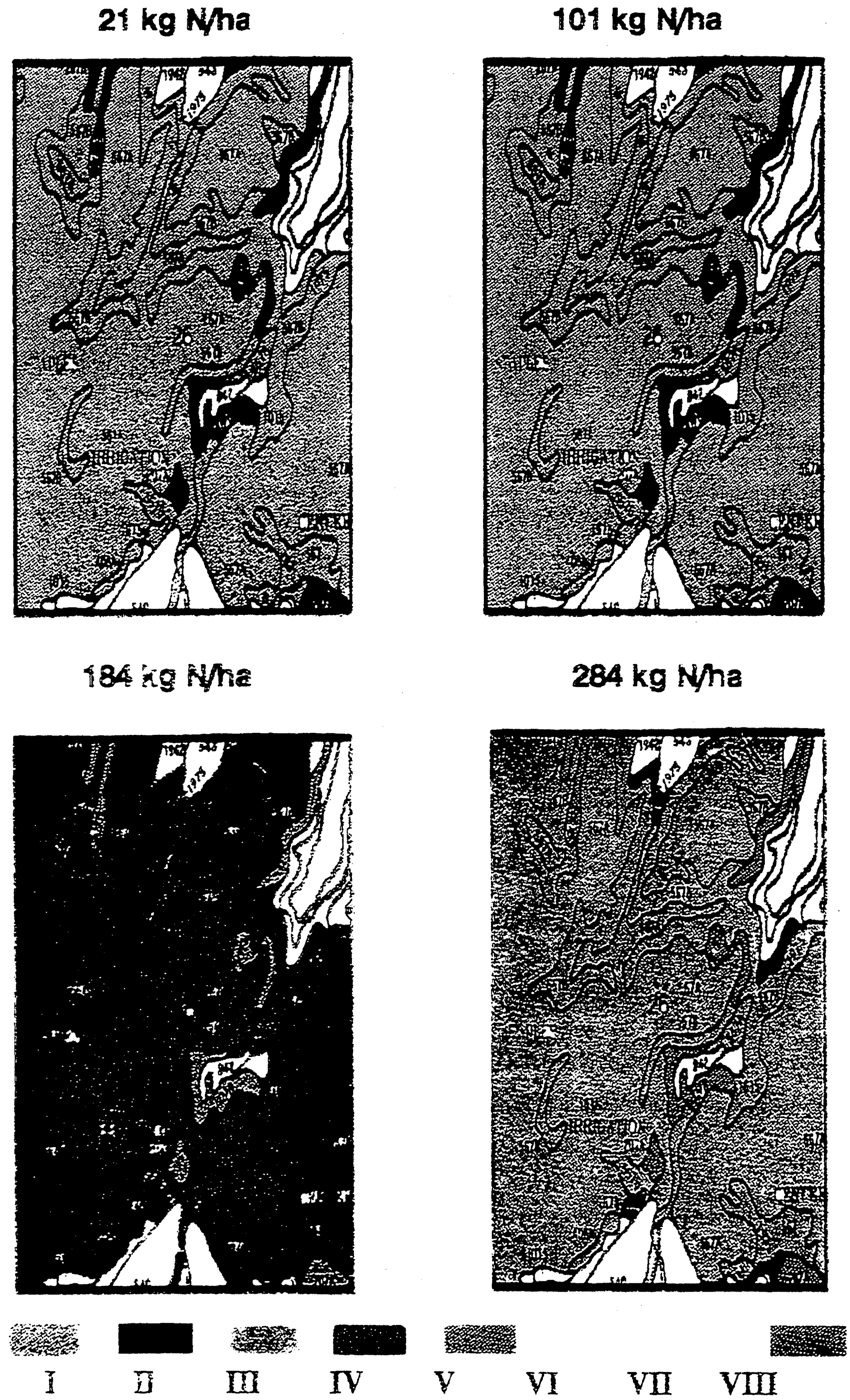

Figure 3-13. Effect of fertilizer application rate on risk characterization of soils to nitrate leaching for an irrigation trigger of 60% and at a cumulative probability of 50% (median year).

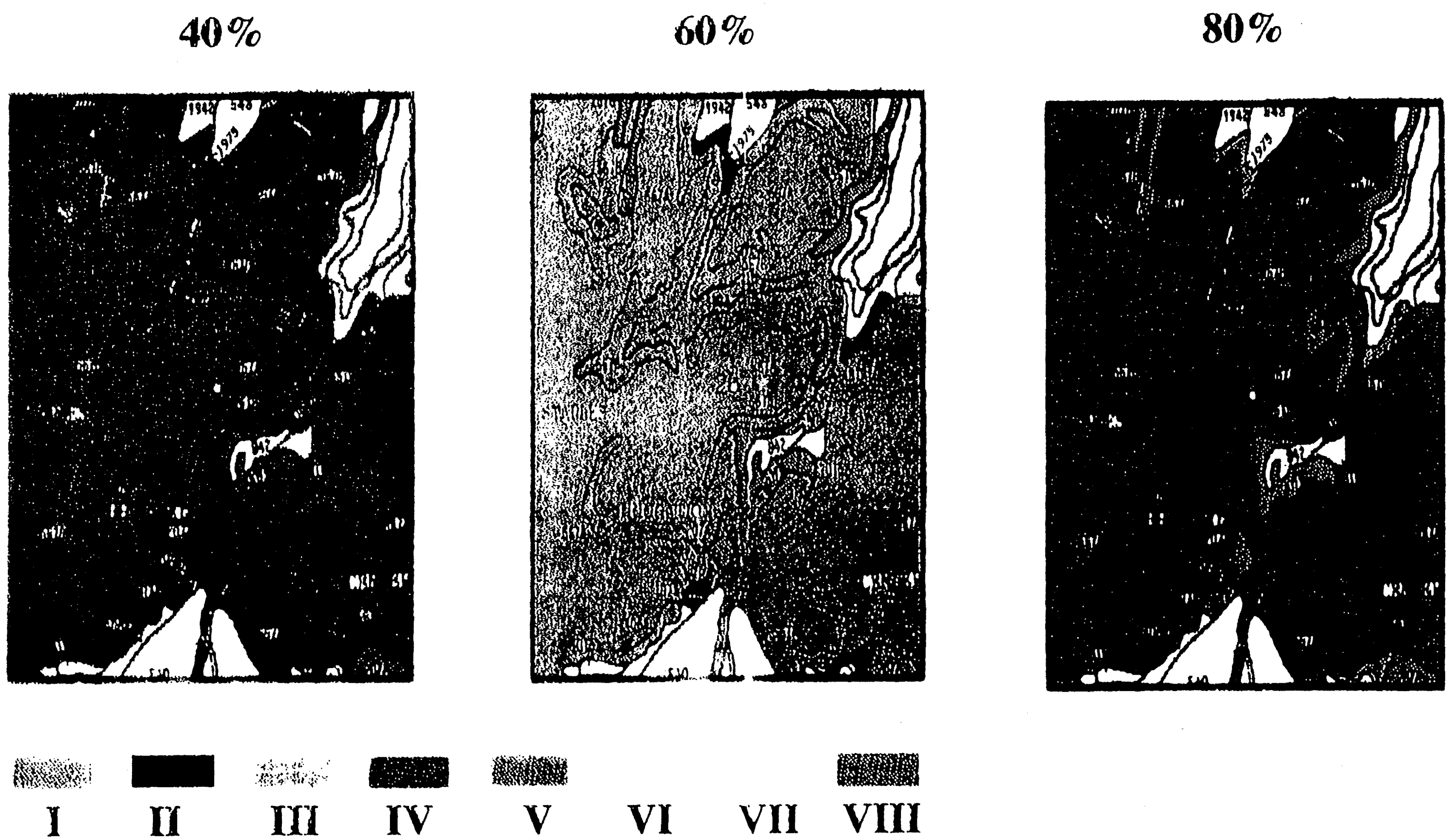

Figure 3-14. Changes in risk indices of soils to nitrate leaching as a function of various irrigation triggers at a fertilizer application rate of 284 kg N/ha and at a cumulative probability of 50% (median year).

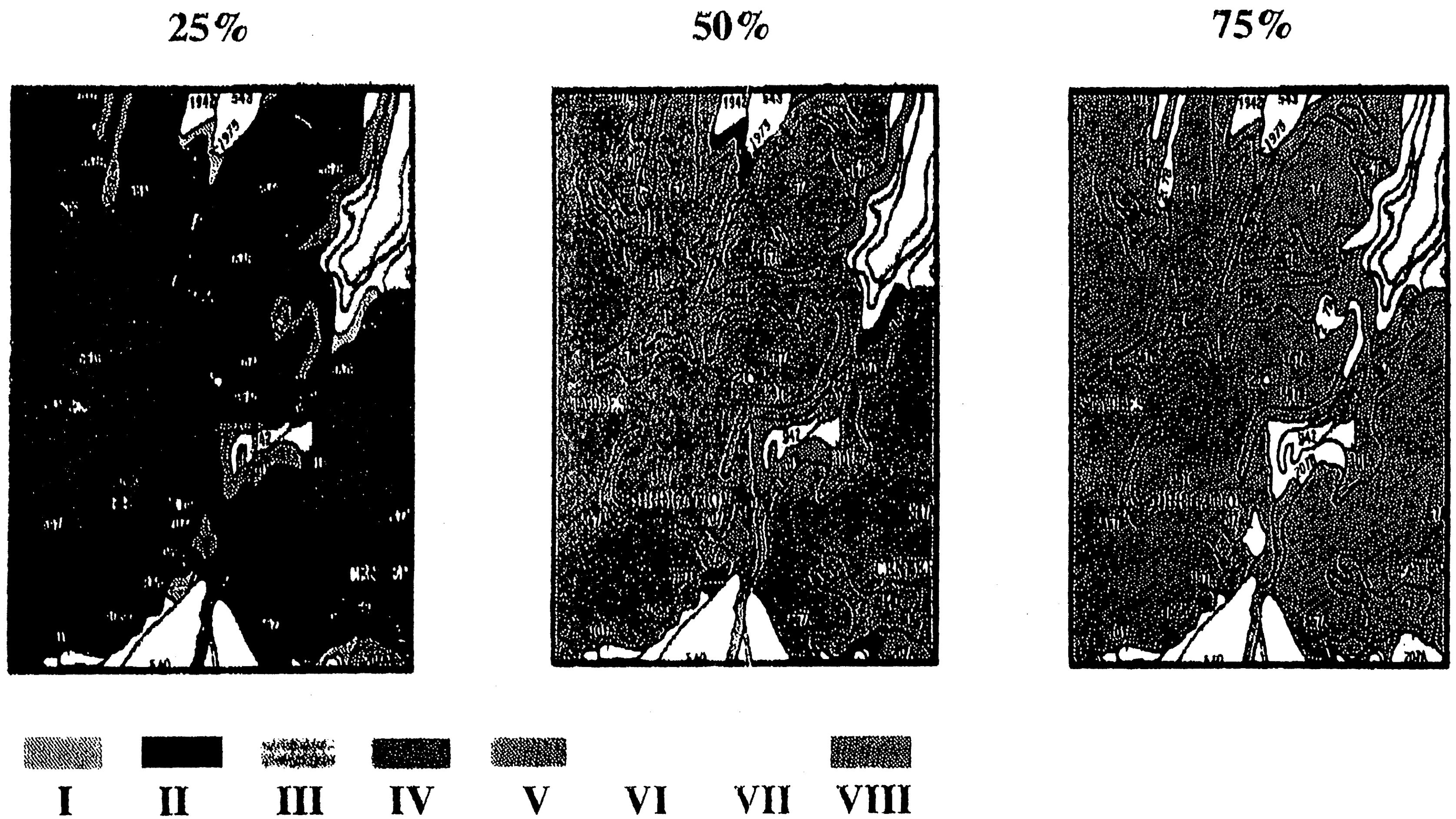

Figure 3-15. Changes in risk indices of soils to nitrate leaching at various cumulative probabilities with an irrigation trigger of 60% and at a fertilizer application rate of 284 kg N/ha.

Chapter 4. SOIL WATER DYNAMICS UNDER GROWING POTATO PLANTS IN SPRINKLER AND DRIP IRRIGATED SOILS

ABSTRACT

It has been shown that rains either alone or in combination with irrigation result in water percolation and nitrate leaching past the root zone in outwash soils of the upper Midwest. This study was conducted to evaluate if subsurface drip irrigation might be a possible alternative in providing substantial unfilled pore space to hold water from unforeseen rains that might occur right after irrigation. Specific objectives of this study were to quantify the differences between sprinkler and drip irrigation systems in a growing potato field in terms of 1) soil wetting and drying patterns, 2) water loss in evapotranspiration (ET) and drainage (DR), and 3) the crop water use coefficients for potato plant for climate of the upper mid-west.

The experiment consisted of measuring hourly soil profile water content with Time Domain Reflectometry probes under growing potato plants in both sprinkler and drip irrigated plots in Verndale sandy loam at Staples, MN. Drip lines were installed at a depth of 25 cm below the soil surface. For each irrigation treatment, 16 TDR probes were installed at 15 intervals both in the vertical and the horizontal directions. Since greater changes in soil water content were expected near the soil surface, more probes were installed near the surface than at deeper depths.

Wetting and drying patterns showed that there was little water movement to the upper parts of the ridge in the drip irrigated plot. Under both furrow and just below the center of the ridge, there was a large change in water content. This large change in soil water content under the furrow was due to greater amount of infiltration as a result of water runoff from the ridge. Large changes in soil water content just below the ridge was due to more water arriving at the base of the plant from stem flow and then some preferential movement through cracks created by the expanding tubers. Small changes in water contents just below the shoulder of the ridge compared to just below the furrow were due to higher runoff from the shoulder of the ridge and thus less water infiltration.

The wetting pattern under drip irrigation in Verndale sandy loam was initially circular around the drip, but developed into an oblong distribution over time due to gravity. Under drip irrigation, soil drying patterns were concentrated in the top center part of the ridge thereby suggesting that most plant roots must be concentrated in the top of the ridge just above the drip. Under sprinkler irrigation, the soil drying pattern was diffused and spread all over the soil profile (20 to 40 cm depth) thereby suggesting that the potato roots must be present throughout.

There was no significant difference in evapotranspiration (ET) between the drip and sprinkler irrigated plots since soil water was not limiting throughout the growing season in both treatments. Seasonal ET for both irrigation treatments averaged 265 mm. This was equivalent to daily average ET of 2.9 mm d^{-1} for both drip and sprinkler treatments. Measured seasonal DR was 136 and 67 mm whereas average daily DR rate was 1.5 and 0.8 mm d^{-1} for the drip and the sprinkler irrigated plots, respectively. The higher seasonal DR from the drip irrigated plot was because of over application of water for the drip irrigated plot. During the calculation water was applied over the total plot area rather than much smaller area around the drip line. The crop coefficient (Kc) for potatoes was nearly 1.0 from middle of June to middle of August for both sprinkler and drip irrigated plots. This is very similar to observations reported in the literature, Kc is

equal to 1.0 after the crop canopy is fully developed. The results of this study provide a better understanding of the wetting and drying patterns of a hill-furrow system under sprinkler and drip irrigated conditions.

INTRODUCTION

Elevated levels of nitrate in surficial aquifers in the Central Sands of Minnesota have been associated with intensive farming (Myette, 1984). Soils in the Central Sands of Minnesota are typically outwash soils that are low in productivity because of low water holding capacity, and associated rapid drainage. Since the precipitation in the area during the growing season is not enough to sustain most agricultural crops, water needs of crops are often met with irrigation from shallow groundwater. One of the major crops of the area is potatoes. Since potato plants are sensitive to water and nitrogen stress, the growers in the area frequently irrigate and often excessively fertilize potatoes to insure its maximum yield and higher quality.

Earlier Pang et al. (1993) and Sexton et al. (1993) showed that water percolation and nitrate leaching in the Central Sands of Minnesota were due to rain either alone or in combination with irrigation. Therefore in order to minimize leaching losses in these soils, it is important that some soil pore space be available to capture water from unforeseen rains.

There are several ways to maintain unfilled soil pore space and thus minimize the impact of unforeseen rains on nutrient leaching. These include: 1) High deficit irrigation such that the period between irrigation is large and thus there is a greater chance of capturing water from unforeseen rains. 2) Irrigating soils to water contents less than field capacity and thus there is some unfilled pore space that can capture water from unforeseen rains. 3) Localizing irrigation to areas of high root density,
and leaving the soil around the plant unfilled to capture unforeseen rains. For soils irrigated with sprinkler irrigation systems, the first two options are appropriate. However, the third option can only be achieved with a drip irrigation system. A study to evaluate the effectiveness of these and other management options to minimize nitrate leaching from soils in the Central Sands of Minnesota has been underway since 1994 (Waddell, 1994). The experiment reported in this chapter is a part of that study.

The most common irrigation method in the Central Sands of Minnesota is center pivot sprinkler irrigation. With this method, water is nearly uniformly applied over the whole field and if irrigated to field capacity, then there is very little storage left to hold additional water from unforeseen rains. Drip irrigation, on the other hand, provides an effective method of localizing the water application in the row and leaving significant storage space in rest of the soil to capture unforeseen rains. With the drip irrigation, not only there will be savings of water but it will also help to minimize nitrate leaching. For potatoes, drip irrigation can be applied either as surface or subsurface irrigation.

With the buried drip, there could be a substantial unfilled pore space both in the potato hill and the furrow to hold water from unforeseen rains that may occur right after irrigation. The depth and placement of drip line relative to the hill is important in order to maximize the availability of water to plant and reduce nitrate leaching from irrigation. Soil drying (water uptake by potato plant) and wetting (rain or drip) patterns both for sprinkler and drip irrigation can be helpful in understanding water movement under a growing potato plant in a ridge-furrow system.

Since drip irrigation is relatively new and has not been extensively used in potato production, there is little information in the literature on the water uptake patterns by a potato plant in drip irrigated soils (Shalhevet et al., 1983). In addition, there is not much information on comparison of the soil wetting patterns between subsurface drip and sprinkler irrigation system under a ridge-furrow configuration. Although, it has been postulated in the literature (Saffigna et al., 1976) that the flux of water entering the soil surface from either rain or sprinkler irrigation will vary with the position along the ridge, no experimental evidence has been provided for such distribution. However, preferential transport of rain or sprinkler applied water along the stem to the base of the potato plant has been given by Saffigna et al. (1976).

Estimates of potato water use are essential in developing irrigation scheduling schemes based on plant water needs. Boisvert et al. (1992) estimated that seasonal water use from June to August by various potato cultivars ranged from 274 to 387 mm during a two year study. In their study, seasonal water use was estimated from the weather data. Lundstrom and Stegman (1977) and Wright and Bergsrud (1986) estimated the potato water use based on air temperature and crop growth stage. In weather driven ET calculations such as by Boisvert et al. (1992),
Lundstrom and Stegman (1977), and Wright and Bergsrud (1986), an essential parameter to estimate crop water use is the crop coefficient. Wright and Stark (1990) used a weighing lysimeter to develop crop coefficient for potatoes grown in a silt loam soil in southern Idaho. Hane and Pumphrey (1984) provided values of crop coefficient for potatoes under Oregon climate conditions. Vitosh (1984) extrapolated literature's values of crop coefficient for potatoes to Michigan climate conditions. Most of the experimental studies for estimating crop coefficients for potatoes have been under arid climates. To the author's knowledge, there is no information on daily water use for potatoes in Minnesota.

The goal of this study was to understand the soil water dynamics with a growing potato plant under drip and sprinkler irrigations. The objectives of this experiment were: 1) to quantify soil wetting and drying patterns under a growing potato plant; 2) to quantify water losses due to evapotranspiration and percolation under both sprinkler and drip irrigation systems; and 3) to determine potato water use coefficients for the climate of upper the Mid-West.

MATERIALS AND METHODS

This experiment was part of a large field study on the effects of fertilizer and irrigation interactions on potato yield and nitrate leaching currently underway at the Staple Irrigation Center, Staples, MN (Waddell, 1994). The soil at the experimental site is a Verndale sandy loam (coarse loamy over sandy, mixed, frigid, Udic Argiboroll). Hydraulic properties of the soil have been given by Sexton (1993) and are summarized in Table 4-1.

Table 4-1. Soil bulk density (ρ_b) and coefficients of van Genuchten's equations that describe water retention and hydraulic conductivity vs. water content relationships for the Verndale sandy loam. The values of the variables in van Genuchten's equations were estimated using the RETC program (van Genuchten et al., 1991).

		variables in van Genuchten's equations†				
Horizon (cm)	ρ_b	θ_s	θ_r	α	n	K_{sat}
	Mg m^{-1}	cm^3 cm^{-3}	cm^3 cm^{-3}	cm^{-1}		mm d^{-1}
Ap (0-26)	1.52	0.395	0.023	0.0431	1.280	1138
Bt (26-40)	1.73	0.333	0.000	0.0104	1.315	331
C (> 40)	1.56	0.412	0.000	0.0702	1.494	2880

† Soil water retention characteristics curve:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha h)^n]^m}$$

Hydraulic conductivity function:

$$K(h) = K_{sat} \frac{(1 - (\alpha h)^{n-1}[(1+(\alpha h)^n]^{-m})^2}{[1+(\alpha h)^n]^{m/2}} \quad ; \quad m = 1 - \frac{1}{n}$$

where θ_s and θ_r are the saturated and residual water contents, respectively; α, n and m are empirical constants; and K_{sat} is the saturated hydraulic conductivity.

The experiment consisted of monitoring soil water content with TDR probes under a growing potato plant in two irrigation treatments of Waddel (1994). The specific irrigation treatments monitored were 30% deficit sprinkler irrigation and subsurface drip irrigation.

TIME-DOMAIN REFLECTOMETRY PROBE LAYOUT

A layout of TDR probes for the drip and the sprinkler irrigation treatments is shown in Figures 4-1 and 4-2, respectively. In each treatment, a total 16 TDR probes were installed at 5 soil depths after potatoes had been planted and a hill had been built over the planted row. All probes were approximately 15 cm apart both vertically and horizontally. The distribution of probes was as follows: first layer (15 cm from the top of the ridge) had 2 probes, second layer (30 cm from the top of the ridge) had 6 probes, third layer (45 cm from the top of the ridge) had 5 probes, fourth layer (60 cm from the top of the ridge) had 2 probes, and the fifth layer (75 cm from the top of the ridge) had 1 probe.

Time line of various cultural practices are given in Waddell (1994). Briefly, the drip lines were installed on April 13, potatoes were planted on April 25, TDR probes were installed on May 10, TDR measurements began on June 12, and the last TDR measurements were taken on September 12. The drip line was installed just above the Bt horizon at 25 cm depth (40 cm from the top of the ridge).

TDR MONITORING SYSTEM

TDR probe readings were recorded every hour using an automated computer based monitoring system. The computer based monitoring system was similar to that described by Spaans and Baker (1993). Software and hardware were modified to accommodate the large number (32 probes) of TDR probes used in this study. In Figure 4-3 is given the schematic diagram of TDR monitoring system.

The TDR probes (Midwest Special Services, Inc., St. Paul, MN) used in this study were 30 cm long stainless steel probes with a 3 cm spacing between two probes (Spaans and Baker, 1993). TDR cable tester (1502B, Tektronix Inc., Beaverton, OR) was connected to an IBM 286 computer through a communication interface (SP232, Campbell Scientific, Inc., Logan, UT). In order to automate the monitoring system, two levels of multiplexers (JFW Industries Inc, Indianapolis, IN) were used in this experiment. The first level composed of four coaxial multiplexers (JFW 1:8) each having 8 output channels connected to a total of 32 probes. The second level multiplexer composed of one coax multiplexer (JFW 1:4) with 4 output channels connected to four 1:8 multiplexers. The two levels of multiplexers were controlled by a relay panel (PCL 885, Cyber research, Inc., New Haven, CT) which was then connected to a computer through a computer board (PCL 720, Cyber research, Inc., New Haven, CT). A self powered Optical Isolator (O.I.) (232SPOP4, B&B electronics Manufacturing Company, Ottawa, IL) was installed between the SP232 and computer in order to isolate the SP232 from the noise generated by AC power grounding of computer. For safety purposes, DC power of TDR system was grounded separately. Software was written so that only one channel in both 1:4 and 1:8 multiplexers was open at any given time to receive and send signals to and from the computer. Computer, TDR Cable Tester, relay panel and batteries were all housed in an insulated wooden cabinet with an air conditioner.

ESTIMATING DRAINAGE AND EVAPOTRANSPIRATION

Daily drainage and evapotranspiration losses were calculated from the hourly change in soil water contents as measured by the TDR probes.

$$CW_h = \sum_{i=1}^{16} (\theta_2 - \theta_1)\ \Delta Z \qquad [1]$$

where CW_h is hourly change in soil profile water storage in soil profile, cm; θ_1 and θ_2 are water contents of probe; and i at t_1 and t_2 hours, respectively, $cm^3 cm^{-3}$; and ΔZ is the thickness of soil layer represented by a TDR probe (15 cm).

The negative values of CW_h represent water loss (WL_h) from the soil profile whereas positive values of CW_h represent water gain (WG_h) in the soil profile.

$$If\ CW_h < 0\ then\ WL_h = CW_h \qquad [2]$$

$$If\ CW_h > 0\ then\ WG_h = CW_h \qquad [3]$$

The summation of hourly negative change in soil water storage over a given day was considered as the daily water loss (WL) both due to drainage and evapotranspiration:

$$WL = \sum_{t=1}^{24} (WL_h) = DR + ET \qquad [4]$$

where DR is daily drainage, mm d^{-1} ; ET is daily evapotranspiration, mm d^{-1}; and t is the time of the day, hour.

In this experiment any water that leached passed the 75 cm depth (deepest TDR probe) was considered as drainage. Drainage consisted of two parts: 1) base flow and 2) percolation. Base flow (BF) was calculated using Darcy's law whereas percolation was calculated from the hourly soil water loss (WL_h) values.

$$BF = K_{sat} K_r(\theta) \left(\frac{\partial h}{\partial z} + 1\right) \qquad [5]$$

where K_{sat} is the saturated hydraulic conductivity, $K_r(\theta)$ is the relative hydraulic conductivity, h is matric potential, z is soil depth and θ is water content. Hydraulic parameters (K_{sat}, $K_r(\theta)$, $h(\theta)$) in Eq. [5] were estimated from the laboratory characterization of soil water retention and the hydraulic conductivity vs. water content relationships (Figures 4-4 and 4-5) and the TDR measured soil water contents. The laboratory measured saturated hydraulic conductivity of the bottom layer (C horizon) was 2880 mm d^{-1} (Table 4-1). Matric potential gradient in the C horizon was estimated separately for the drip and the sprinkler irrigated plots.

Base flow calculations in the drip irrigated plot were divided into two groups: 1) within the zone of influence of drip irrigation, and 2) outside the zone of influence of drip irrigation. Base flow in the zone outside the area of influence of drip irrigation was assumed to be same as the base flow in the sprinkler irrigated plot.

Base flow within the zone of influence of drip irrigation was calculated using the long-term base water contents in the C horizon as measured by TDR probes #14 and #16 (Figure 4-1). On the average, the base water contents at TDR probes position #14 and #16 were 0.125 and 0.100 $cm^3 cm^{-3}$, respectively (Figure 4-6a). Using the soil water retention curve for the C horizon (Figure 4-4), these water contents translate to a matric potential of -100 and -200 cm at probes position #14 and #16, respectively. This is equal to a matric potential gradient of (-200-100)/ (-15) = 6.7. Thus with relative hydraulic conductivity at an average water content of 0.113 equal to $4*10^{-5}$ (Figure 4-5) and Ksat of 2880 mm d^{-1}, the hydraulic conductivity of the C horizon at base water content is 0.115 mm d^{-1}. Multiplying unsaturated hydraulic conductivity by hydraulic gradient (Eq. [5]) results in a Darcy's flux or BF of 0.8 mm d^{-1}.

For the sprinkler irrigation, both TDR probes #30 and #32 (Figure 4-6b) showed no change in the base water contents over time and the long-term average water content as measured by both TDR probes #30 and #32 was 0.09 $cm^3 cm^{-3}$. This was equivalent to a zero matric potential gradient in the C horizon for the sprinkler irrigated plot. The base flow in the sprinkler irrigated plot was thus mostly due to the gravitational gradient. With relative hydraulic conductivity at an average water content of 0.09 $cm^3 cm^{-3}$ equal to 1×10^{-5} (Figure 4-5) and Ksat of 2880 mm d^{-1}, the hydraulic conductivity of the C horizon at base water content is 0.029 mm d^{-1}. Multiplying unsaturated hydraulic conductivity by hydraulic gradient (Eq. [5]) results in a Darcy's flux or BF of 0.029 mm d^{-1} for the sprinkler irrigated plot.

In Table 4-2 are shown the parameters of Darcy's flux and the base flow for both drip and sprinkler irrigated plots. As stated earlier, base flow from the zone outside the influence of drip irrigation was assumed to be same as that from the sprinkler irrigated plot.

Table 4-2. Calculation of Base flow percolation for both drip and sprinkler irrigated plot.

	Drip Irri. plot		Sprinkler Irri. plot
	Within range†	Outside range‡	
Khat, mm d^{-1}	2880	2880	2880
$K(\theta)$	0.00004	0.00001	0.00001
Average water content, $cm^3 cm^{-3}$	0.113	0.09	0.09
Gravitational Gradient, mm mm^{-1}	1.0	1.0	1.0
Matric Potential Gradient, mm mm^{-1}	6.7	0.0	0.0
Base flow, mm d^{-1}	0.818	0.029	0.029

† Within the range of influence of drip irrigation.
‡ Outside the range of influence of drip irrigation.

Daily ET values were calculated from WL_h. The procedure involved subtracting the hourly base flow (BF_h) from WL_h to calculate hourly ET (ET_h). ET_h values were then compared against the maximum hourly water loss (ET_{hmax}) on any given day. If an ET_h value was more than ET_{hmax}, then ET_h for that hour was set equal to ET_{hmax}, and the difference between ET_h and ET_{hmax} (ET_h -ET_{hmax}) was considered as hourly percolation (DR_h). If ET_h was less than ET_{hmax}, then hourly ET= ET_h. Hourly base flow (BF_h) was estimated as the daily base flow divided by 24 hours (BF/24). Mathematically, the above algorithm can be described as follows:

$$BF_h = \frac{BF}{24} \qquad [6]$$

$$If\ (WL_h - BF_h) < ET_{hmax}\ then\ ET_h = WL_h - BF_h,\ DR_h = BF_h \qquad [7]$$

$$If\ (WL_h - BF_h) > ET_{hmax}\ then\ ET_h = ET_{hmax},\ DR_h = WL_h - ET_{hmax} \qquad [8]$$

The daily ET and DR were calculated using the following algorithm.

$$If\ \sum_{t=1}^{24} ET_h < ET_{Pen}\ then\ ET = \sum_{t=1}^{24} ET_h,\ DR = \sum_{t=1}^{24} DR_h \qquad [9]$$

$$If \sum_{t=1}^{24} ET_h > ET_{Pen} \text{ then } ET=ET_{Pen}, \quad DR=\sum_{t=1}^{24} DR_h + \sum_{t=1}^{24} ET_h - ET; \qquad [10]$$

where ET_{Pen} is the potential ET calculated using the Penman method, mm d^{-1}.

ET_{Pen} was calculated using the FAO-modified Penman equation (Doorenbos and Pruitt, 1977) by the SCS-Scheduler program (Shayya and Bralts, 1994). Since the weather data gathered at the Staples Weather station was not designed for use with the SCS-Scheduler program, a daily weather input data file was created to meet the requirements of weather input data file of the SCS-Scheduler program. The data file consisted of four values of 6 hour average wind speed, daily value of minimum and maximum air temperatures, daily values of minimum and maximum air relative humidity, daily mean wind speed, daily total solar radiation (R_s), and daily net solar radiation (R_n). The 6 hour average wind speed was calculated from six hourly wind speed values. Since there was no daily R_n measured at the Staples weather station, the R_n was calculated as follows:

$$Rn=Rn_s-Rn_l \qquad [11]$$

$$Rn_s=(1-\alpha)\ R_s \qquad [12]$$

where Rn_s and Rn_l are daily net shortwave solar radiation and daily net long wave radiation, respectively, (W m^{-2}). R_s is daily total solar radiation (W m^{-2}), and α is albedo. The value of α was taken as 0.23 as suggested for most green crops by Monteith and Unsworth (1990). In general, α varies before the crop canopy closes. Since the TDR measurements were started on June 12 not long before potato canopy closed (June 23), we used only one value of α in our calculation of Rn_s.

Rn_l was calculated using the procedure given in Shayya and Bralts (1994).

$$Rn_l=f(T)\ f(e_d)\ f(SunRatio) \qquad [13]$$

$$f(T)\ =\ \sigma\ T_k \qquad [14]$$

$$f(e_d)\ =\ 0.34\ -\ 0.044\ \sqrt{e_d} \qquad [15]$$

$$f(SunRatio)\ =\ 0.1\ +\ 0.9\ SunRatio \qquad [16]$$

where σ is Stefan-Boltzman's constant, equal to 1.97 10^{-10} mm d^{-1}, T_k is air temperature in Kelvin, and e_d is actual vapor pressure, mbar. SunRatio is the ratios of actual sun shine hour to the maximum possible sun shine hour on any given day at Staples Irrigation Center, Staples, MN. SunRatio was calculated using the following regression equation:

$$SunRatio = 0.102 + 0.0013\ R_s \qquad R^2=0.64 \qquad [17]$$

Equation [17] was derived using the daily values of the sun shine hour data from May 1 to October 1, 1994 from the Minneapolis airport weather station and the solar radiation data taken from St. Paul campus weather station. The use of this equation to calculate Rn_l assumes that the relationship between sun shine hour and solar radiation at Staples, MN would not be different from that at the Twin Cities of St. Paul and Minneapolis.

ET_{hmax} was calculated as a proportion of the ET_{Pen} on any given day. The proportion was equal to the ratio of ET_{hmax} to ET_{Pen} on July 15.

$$ET_{hmax} = ET_{Pen}\,\frac{ET_{hmax}(July15)}{ET_{Pen}(July15)} \qquad [18]$$

where ET_{hmax} is hourly maximum ET on any given day, ET_{hmax} (July 15) is hourly maximum ET on July 15, ET_{Pen} is Penman's potential ET on any given day, and ET_{Pen} (July 15) is Penman's potential ET on July 15. ET_{Pen} and ET_{hmax} on July 15 was chosen as a reference date for the ratio in Eq. [18] because there was no rain or irrigation within last 24 hours. This insured that all water loss on July 15 occurred as ET plus BF (Figure 4-7). This procedure assumes that the higher daily potential evapotranspiration is a result of higher hourly evapotranspiration. This assumption is valid for days when soil moisture is not limiting.

Just to insure that there was no water stress during the growing season, we under took the following analysis. We calculated the crop available soil water capacity (ASWC) of all three horizons (Table 4-3). ASWC is defined as the difference in water content between field capacity (ψ_m = -33 k Pa) and permanent wilting point (ψ_m = -1500 k Pa). Since there is some literature that suggests that the maximum yield of high quality potatoes can be achieved when soil water content is above 50% of the ASWC (Singh, 1967), we compared our TDR measurements in Figures 4-8 through 4-15 with 50% ASWC. Table 4-3 shows that water contents were above the 50% ASWC and were thus non-limiting for potatoes in the experiment.

Table 4-3. FC, PWP, ASWC and water content respect to the 50% of ASWC for Ap, Bt, and C horizons.

Horizon	FC	PWP	ASWC	†50% of ASWC
Ap	0.17	0.05	0.12	0.11
Bt	0.21	0.06	0.15	0.14
C	0.10	0.03	0.07	0.07

† water content at the 50% of available soil water.

CROP COEFFICIENT

Daily values of crop coefficient (Kc) were calculated as a ratio of the calculated daily ET to daily ET_{Pen} (Doorenbos and Kassam, 1979):

$$Kc = \frac{ET}{ET_{Pen}} \qquad [1]$$

INFILTRATION

At the end of the growing season, an additional experiment was undertaken to test the response of TDR to water and solute movement. This was done to see if TDR can pick up preferential leaching of water. A 1 m x 1 m area around the TDR site in drip irrigated plot was diked and then flooded with 200 liters of 0.8 g L^{-1} KBr solution. TDR response was monitored as the water moved through the soil. In the first hour, three readings were taken for each TDR probe. After the first hour, the TDR probes were monitored every hour.

RESULTS AND DISCUSSIONS

SOIL WATER DYNAMICS UNDER A GROWING POTATO PLANT

Temporal changes in soil water content measured by TDR probes under a potato hill are graphed in Figures 4-8 through 4-11 for the drip irrigated plot and Figures 4-12 through 4-15 for the sprinkler irrigated plot. The following discussion describes the extent of the changes in soil water content as a function of probe position.

DRIP IRRIGATED PLOT

In the drip irrigated plot, the first layer of TDR probes (#1 in Figure 4-8 and #2 in Figure 4-9) responded only to rainfall and there was not much noticeable response to drip irrigation. This suggested that there was not much movement of water from the drip tube to the upper region of the ridge. During rainfall, there was a larger change in soil water content at probe position #1 as compared to probe position #2. Since the potato plant was located directly above probe #1 and there were also several cracks created in the soil by the expansion of potato tubers above this probe, we believe this difference in water content between probe position #1 and #2 was due to a combination of stem flow and then preferential water flow through soil cracks to probe position #1.

Probe #3 (Figure 4-10) located at the shoulder of the ridge had a similar response to rainfall as probe #1. However, the magnitude of changes in soil water content at probe position #3 was much smaller than that at probe position #1. This is because most rain water ran off the soil surface at the shoulder of the ridge (above probe position #3) and which resulted in less water entry into the soil. These results are similar to the observations of Saffigna and Tanner (1976) that there was less water infiltrating at the shoulder of the ridge than in the furrow. In general, water contents at probe position #1 were lower than that at probe position #3. This difference in water content is because of increased root activity at probe position #1 and thus higher water loss due to root uptake just below the potato plant.

Probe #5 (Figure 4-10) located exactly above the drip line showed large changes in soil water content in response to the water addition from the drip. Probes #4 and #6 (Figure 4-10) located about 20 cm away from the drip line also showed some response to drip irrigation but the change in water content at both these locations was much smaller as compared to probe position #5. Probes #9 and #11 (Figure 4-11), a slightly closer to the drip line, responded similarly to the water addition from the drip as probes #4 and #6. As expected, the soil water contents were higher at probe positions #4 and #9 as compared to probe positions #6 and #11, due to increased root activity and thus higher water loss just below the ridge.

Since probe #10 (Figure 4-8) was located exactly under the drip line, it showed the greatest change in soil water content on water addition from the drip line. Probe #14 (Figure 4-8) located just below probe #10, responded similar to probe #10 but the magnitude of changes in soil water content on water addition were smaller. This is expected because the distance between probe #14 to drip line was greater than the distance between probe #10 and the drip line. In other words, some water was being retained in pore space between probe #10 and #14 and thus less water was arriving at probe position #14. In addition, probe #14 was located in a rapidly draining, low water holding capacity coarser texture C horizon as compared to probe #10 which was located in Bt horizon that had lower hydraulic conductivity and higher water holding capacity. Probe #16 (Figure 4-8) located at 33 cm below the drip line malfunctioned after 227 (August 15) day of the year (DOY). Water content at probe position #16 showed that the probe responded to water application from the drip. Since probe #16 was located at 75 cm below the top of the ridge, far below the potato rooting depth (60 cm), it was assumed that water in this layer was most probably lost in percolation.

The distance between probe #15 (Figure 4-9) to drip line was about the same as that of probe #2 (Figure 4-9), however because of gravity, the response of probe #15 to drip irrigation was quite distinct as compared to probe #2. Probes #8 (Figure 4-10) and #13 (Figure 4-11) showed a similar pattern of changes in soil water content in response of rainfall as probe #3 (Figure 4-10). However, the magnitude of changes in soil water content at probe positions #8 and #13 were higher than that of probe #3. This is because probes #8 and #13 were located just below the furrow where all the runoff from the ridge concentrated as compared to probe #3 which was located below the shoulder where water ran off.

In summary, there was not much water movement to the upper region of the ridge on water application from the drip. Probes located at the same distance around the drip responded similarly but the changes in water content were higher for probes located below the drip than above due to the gravitational effects. This resulted in an oblong shaped water distribution pattern around the drip (next section). As expected, water content changes during rainfall were smaller under the shoulder of the ridge than in the furrow or the ridge itself. Larger changes in soil water content under furrow were due to higher infiltration of water that ran off from the ridge. Large changes in water content just below the surface of the ridge were due to water that arrived at the soil surface as stem flow and then moved preferentially through the cracks created by expanding tubers.

SPRINKLER IRRIGATED PLOT

Being closest to the water source, first layer (15 cm) of TDR probes at the sprinkler irrigation site (probe #18 in Figure 4-12 and #17 in Figure 4-13) showed the largest change in soil water content on surface water addition either from sprinkler irrigation or rainfall. With an increase in soil depth, the response of various probes to water addition decreased (Figure 4-13). For example, the probe in the second layer (30 cm, probe #21) had smaller response to surface water addition than the probes (probe #17 and 18) in the first layer (15 cm). However, there were some differences among various probes in the second layer depending upon their position with respect to the microrelief of the ridge. For example, probe #19 located at the shoulder of the ridge had a small response to water addition (Figure 4-14). Soil at probe position #20 had lower water contents than at probe position #19 because of more root activity (Figure 4-14). At probe position #23 (Figure 4-14), there was a slightly greater change in water contents than at probe positions #20 and #21. This was because probe #23 was located close to the furrow where there may have been greater infiltration from runoff accumulated after heavy rains and irrigations. Magnitude of changes in soil water content at probe position #22 were in between the magnitude of changes at probes position #21 and #23. In general, the base water contents in the second layer followed the pattern: probe #21 < probe #20, and probe #19 < probe #22 < probe #23 (Figure 4-14). This is similar to the patterns observed in the drip irrigation. Greater change in water contents at probe position #17 and #18 on water application were possible due to stem flow and then preferential movement through cracks created by the expanding tubers. Lower base water in probe position #21 were due to higher root activity and thus higher root water uptake just below the ridge.

As expected, in the third layer (45 cm), there was a smaller response to surface water addition than that of the second layer (Figure 4-15 vs. Figure 4-14). Water contents at probe position #26 (Figure 4-15) were consistently lower than the water contents at all positions in the second layer. This was due to less water percolation from the above layers and possibly due to greater root activities and thus more water uptake from the 45 cm depth. Higher base water content at probe positions #27 and #28 as compared to probe position #26, reflected lower root activity at probe positions #27 and #28. On the other hand, lower water content at probe position #29 as compared to probes #27 and #28 reflected less percolation of water from the soil surface because of compaction caused by the passing tractor during an application of pesticide.

The response of 4th (60 cm) and 5th (75 cm) layer of probes, #30 and #31 (Figure 4-13) to surface water addition from DOY 215 to 255 was small thereby indicating very little percolation of water arriving at 60 and 75 cm depths from the upper layers. A slight increase in water content at probe position #32 before DOY 215 indicated some percolation of water past the root zone.

In summary, the soil below the ridge had the greatest change in water content on water addition either from sprinkler irrigation or from rainfall. After rainfall or irrigation, water contents below the shoulder of the ridge were less than that directly under the ridge, thereby suggesting stem flow and then preferential movement of water through cracks formed by the expansion of potato tubers. At the rates the water was applied at soil surface in this experiment, there was very small water percolation past the root zone.

CHARACTERIZATION OF WETTING AND DRYING PATTERNS

Examples of wetting and drying patterns in Verndale sandy loam from drip and sprinkler irrigation are shown in Figures 4-16 through 4-20. Wetting and drying patterns refer to the change in water content from an initial water distribution.

Wetting Patterns:

An example of the wetting patterns in Verndale sandy loam on application of water through a drip line is shown in Figure 4-16. This change in water content is relative to the water distribution at 1900 hours on July 12. In this example, 4 mm of water was applied in a 12 minute period starting at 2000 hours on 12 July through a drip line. At (2100 hours), soil wetting was nearly circular around the drip, but with an increase in time (2200 and 2300 hours), the wetting patterns developed into an oblong shape distribution due to gravity. The extent of the water distribution reached its maximum in two hours (2200 hours) after the start of the drip irrigation. This suggests that water may be just temporarily sitting in and around the drip line and then slowly entering the soil after the drip irrigation was shut off. Two hours after drip irrigation, water content around the drip line started to decrease due to lateral spreading. Twenty-four hours (2000 hours, July 13) after water application, the influence of drip irrigation was almost unnoticeable.

In Figure 4-17 is shown an example of the soil wetting pattern in the drip irrigated plot from a 16 mm of rainfall. The change in water content in this example is relative to the water distribution at 2100 hours on July 18. There was 1, 9, and 6 mm of rain fell during 1600, 1700, and 1800 hours on July 18, respectively. As is evident from Figure 4-17, the biggest change in soil water content first occurs slightly to the left of the center of the ridge. Since potato plants were also off-set to the left of the ridge, this change in water content suggests that the water entered the soil surface near the base of the potato plant. In other words, there was an occurrence of stem flow. Over time (2200-2400 hours) on July 18, the wetting progressed as an oblong distribution due to gravity. Within 2 hours (0100 hours on July 19), soil reached its maximum water content and from then on there was a decrease in water content but an increase in depth of wetting due to lateral and vertical water distribution. Nineteen hours (1700 hours, July 19) after rainfall, the influence of rainfall was much reduced.

In Figure 4-18 is shown an example of the soil wetting pattern in the sprinkler irrigated plot from the same rainfall as shown in Figure 4-17 (16 mm). Compared to the drip irrigated plot, water entered the soil slightly away to the right from the center of the ridge near the base of the potato plant, again suggesting stem flow. Water content distribution in Figure 4-18 shows lateral flow at about 25 cm depth, most probably due to the presence of Bt horizon.

Drying Patterns:

Soil drying and water uptake patterns on July 12, 1994 in the drip irrigated plot are shown in Figure 4-19. There was no occurrence of irrigation and rainfall in this plot in the previous day. Soil drying patterns were concentrated in the top center of the ridge suggesting potato roots were concentrated in the top center of ridge just above the drip.

In Figure 4-20 is shown the soil drying patterns on July 12, 1994 in the sprinkler irrigated plot. Compared to the drip irrigated plot, drying was diffused and spread all over the soil profile in the sprinkler irrigated plot. This suggests that the potato roots must be some what uniformly spread all over the root zone (20 to 40 cm) for the sprinkler irrigated plot compared to the drip irrigated plot.

DRAINAGE AND EVAPOTRANSPIRATION

Daily precipitation, irrigation and calculated daily ET and DR for drip and sprinkler irrigation plots are graphed in Figures 4-21 and 4-22, respectively. A comparison of the seasonal total evapotranspiration (ET_s), average daily ET (ET_d), seasonal total drainage (DR_s), and average daily drainage (DR_d) between drip and sprinkler irrigated plots from 12 June through 12 September 1994 at Staples, MN is given in Table 4-4. The seasonal ET_s and DR_s values were calculated by adding up the daily ET and DR values (Eqs. [9] and [10]) from 12 June through 12 September, 1994. The average daily ET and DR were calculated by dividing the seasonal ET and DR by 92 days (12 June to 12 September).

In general, there was not much difference in seasonal evapotranspiration (ET_s) or average daily evapotranspiration (ET_d) between the drip and the sprinkler irrigated plots since soil water was not limiting for crop growth throughout the growing season in both plots. Seasonal ET averaged for both irrigation treatments was about 265 mm with daily average of 2.9 mm d^{-1}. There was a large difference in the amount of drainage between the drip and the sprinkler irrigated plots. Seasonal drainage (DR_s) were 136 and 67 mm for the drip and the sprinkler irrigated plots, respectively. Average daily drainage (DR_s) were 1.5 and 0.8 mm d^{-1} for the drip and the sprinkler irrigated plots, respectively. Higher drainage from the drip irrigated plot was a result of over applications of water for the drip irrigated plot. The amount of water for drip irrigation was calculated assuming water application over the total plot area rather than one half of the area around the drip line.

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Table 4-4. Comparison of calculated seasonal total evapotranspiration (ET_s), average daily evapotranspiration (ET_d), seasonal total drainage (DR_s), and average daily drainage (DR_d) between the drip and sprinkler irrigated plots from 12 June through 12 September, 1994, at Staples, MN.

	Et_s	ET_d	DR_s	DR_d	$ET_{s(Pen)}$	$ET_{d(Pen)}$
	mm	mm d^{-1}	mm	mm d^{-1}	mm	mm d^{-1}
Drip	260	2.9	136	1.5	367	4.1
Sprinkler	271	3.0	67	0.8	367	4.1

$ET_{s(Pen)}$ is the seasonal total potential seasonal ET (Penmen method), and $ET_{d(Pen)}$ is daily potential ET (Penmen method).

wetting front velocity compared to the measured pore water velocity suggests that there must have been some alternative paths for rapid water movement. Since water was ponded at the soil surface for 40 minutes, one such possibility is the preferential transport through macropores formed by decaying roots of previous crops (Perillo, 1995).

Table 4-5. Pore water velocity for Ap, Bt, and C horizons.

Horizon	†Ksat cm min^{-1}	Porosity cm^3 cm^{-3}	Pore water Velocity cm min^{-1}
Ap	0.079	0.44	0.186
Bt	0.023	0.36	0.064
C	0.200	0.42	0.476

† saturated hydraulic conductivity of soil the horizon.

In Figure 4-26 is shown the changes in soil water contents as measured with TDR probes under natural rainfall or sprinkler irrigation conditions. For three rainfalls of 1.27, 0.13 and, 0.02 cm over a three hour period, TDR measurements show that it took 5 hours for rain water to reach a depth of 60 cm (Figure 4-26a). This is equivalent to a wetting front velocity of 60/5x60=0.2 cm min^{-1}. For a sprinkler irrigation of 1.5 cm applied in about one hour period, it took about 4 hours for the water to reach a depth of 75 cm (Figure 4-26b). This is equivalent to a wetting front velocity of 75/4x60=0.3 cm min^{-1}. These wetting front velocities show that times when suction should be applied to suction tubes samplers for water sampling would depend upon the rate at which the water is applied at the soil surface. If the soil surface is flooded, to capture solution for chemical analysis the samplers at the 75 cm depth should be under suction within 38 minutes of the start of the wetting event. For sprinkler irrigation of 1.5 cm hr^{-1}, samplers at 75 cm depth should be under suction within 4 hours after the start of water application.

In summary, the above observations suggest water samples collected one hour after flood irrigation may miss the nutrients that are carried to the 75 cm depth with the wetting front. However, the sampling interval depends upon the soil water holding capacity (measuring depth and soil texture) and rainfall or irrigation intensity. The larger the water holding capacity of soil and the smaller the rainfall intensity, longer is the time interval before the solution samples needed to be collected. Conversely, the smaller the soil water holding capacity (9 cm for this soil) and the larger the rainfall intensity (greater than 0.5 cm min^{-1}), the shorter the sampling interval in order to capture nutrients. In our infiltration experiment, the TDR measurement time interval was 38 minute in the first hour. This suggests that majority of water added at the soil surface could have passed 75 cm depth before the TDR probes measurement were even started. This explains why the cumulative amount of soil water gained (8 cm) calculated based on water content measured with TDR probes is much less than the amount of water added as KBr solution (20 cm).

CONCLUSIONS

The Kc curve for potatoes is not available for Minnesota conditions. The curves developed in this study will be useful to researchers and irrigators in designing irrigation scheduling schemes for potatoes in Minnesota.

REFERENCES

Boisvert, J. B., L. M. Dwyer, and M. Lemay. 1992. Estimation of water use by four potato (*Solanum tuberosum L.*) cultivars for irrigation scheduling. Canadian Agri. Engin. 34(4):319-325.

Doorenbos, J., W. O. Pruitt. 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper No. 24, Rome, Italy.

Doorenbos, J. and A. H. Kassam. 1979. Yield response to water. FAO Irrigation and Drainage Paper No. 33, Rome, Italy.

Hane, D. C., and F. V. Pumphrey. 1984. Yield evapotranspiration relationships and seasonal crop coefficients for frequently irrigated potatoes solanum-tuberosum cultivar Russet-Burbank. Am. Potato J. 61: 661-668.

Larsen, D. C. 1984. Simplifying potato irrigation scheduling-the Idaho program. Am. Potato J. 61: 215-227.

Lundstrom, D., and E. Stegman. 1977. Checkbook method of irrigation scheduling. ASAE paper NCR 77-1001, ASAE, St. Joseph, MI.

Monteith, J. L. and M. H. Unsworth. 1990. Principles of environmental physics. 2nd Ed. Routledge, Chapman and Hall.

Myette, C. F. 1984. Groundwater quality appraisal of sand plain aquifers in Hubbard, Morrison, Otter tail, and Wadena counties, Minnesota. U.S. Geological survey. Water-Resources Investigations Report 84-4080. St. Paul, MN.

Pang, X. P., S. C. Gupta, J. F. Moncrief, C. J. Rosen and H. H. Cheng. 1993. Risk characterization of Minnesota outwash soils to nitrate leaching. Report to the legislative Commission on Minnesota Resources. St. Paul, MN.

Perillo, C. A. 1995. Solute transport in sandy soils: potato management modeling and field evaluation of preferential flow mechanisms using a dye tracer. A PhD thesis, the University of Minnesota, St. Paul, MN.

Saffigna, P. G., C. B. Tanner, and D. R. Keeney. 1976. Non-uniform infiltration under potato canopies caused by interception, stemflow, and hilling. Agron. J. 68:337-342.

Sexton, B. T. 1983. Influence of nitrogen and irrigation management on corn and potato response and nitrogen leaching. M.S. thesis, Univ. of Minn., St. Paul, MN.

Shalhevet, J., D. Shimshi, and T. Meir. 1983. Potato irrigation requirements in a hot climate using sprinkler and drip irrigation. Agron. J. 75:13-16.
Shayya, W. H. and V. F. Bralts. 1994. Guide to SCS-Microcomputer irrigation scheduling package (SCS-Scheduler Ver. 3.00), Michigan State University, East Lansing, MI.

Singh, G. 1969. A review of soil water relations in potatoes. Am. Potato J. 46: 398-403.

Spanns, E. J. and J. M. Baker. 1993. Simple Baluns in Parallel Probes for Time Domain Reflectometry. Soil Sci. Soc. Am. J. 57:668-673.

van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892-898.

van Genuchten, M. Th., F. J. Leij and S. R. Yates. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils. Technical report #: EPA /600/ 2-91/065. US-EPA.

Vitosh, M. L. 1984. Irrigation scheduling for potatoes in Michigan. Am. Potato J. 61: 205-213.4.

Waddell, J. 1994. Evaluation of drip and sprinkler irrigation and N management schemes on potato production and N leaching losses. PhD thesis research in progress.

Wright, J. and F. Bergsrud. 1986. Irrigation Scheduling checkbook method. AG- FO-1322. Minn. Ext. Serv., Univ. Minn., St. Paul, MN.

Wright, J. L. and J. C. Stark. 1990. Potato. In: B. A. Stewart and D.R. Nielsen (Eds.). Irrigation of agricultural crops. Agronomy 30. Am. Soc. of Agron., Madison, WI. pp 859-888.

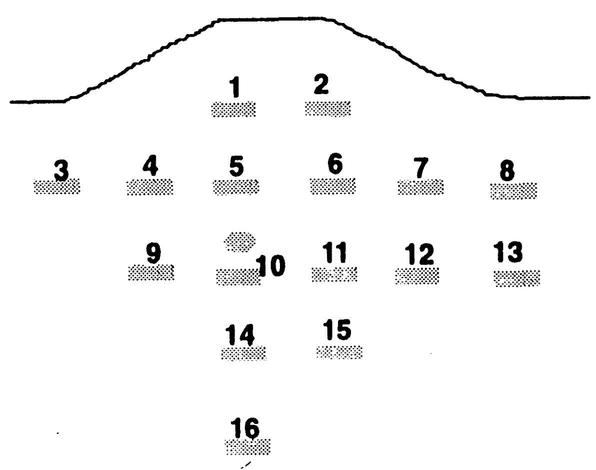

Figure 4-1. The layout of TDR probes for the drip irrigated plot.

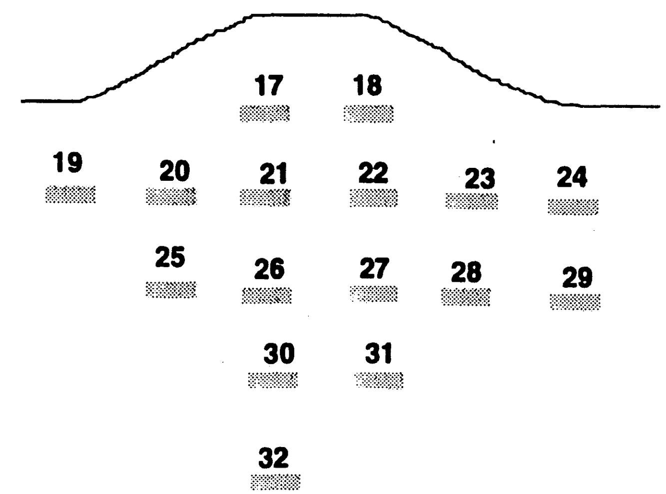

Figure 4-2. The layout of TDR probes for the sprinkler irrigated plot.

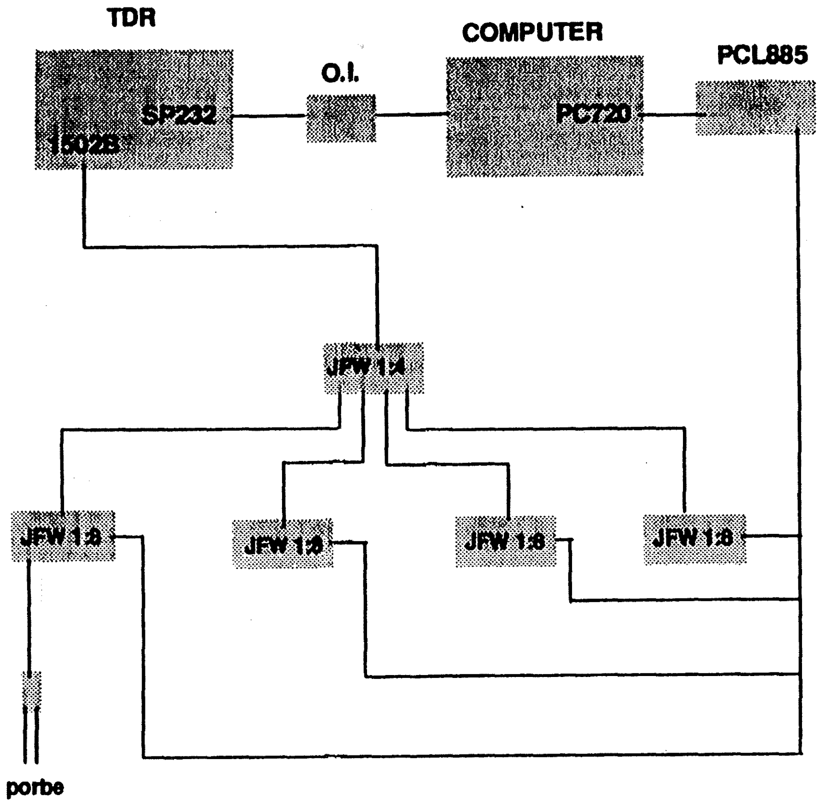

Figure 4-3. Schematic diagram of the components of the TDR system used in the field experiment to measure soil water content.

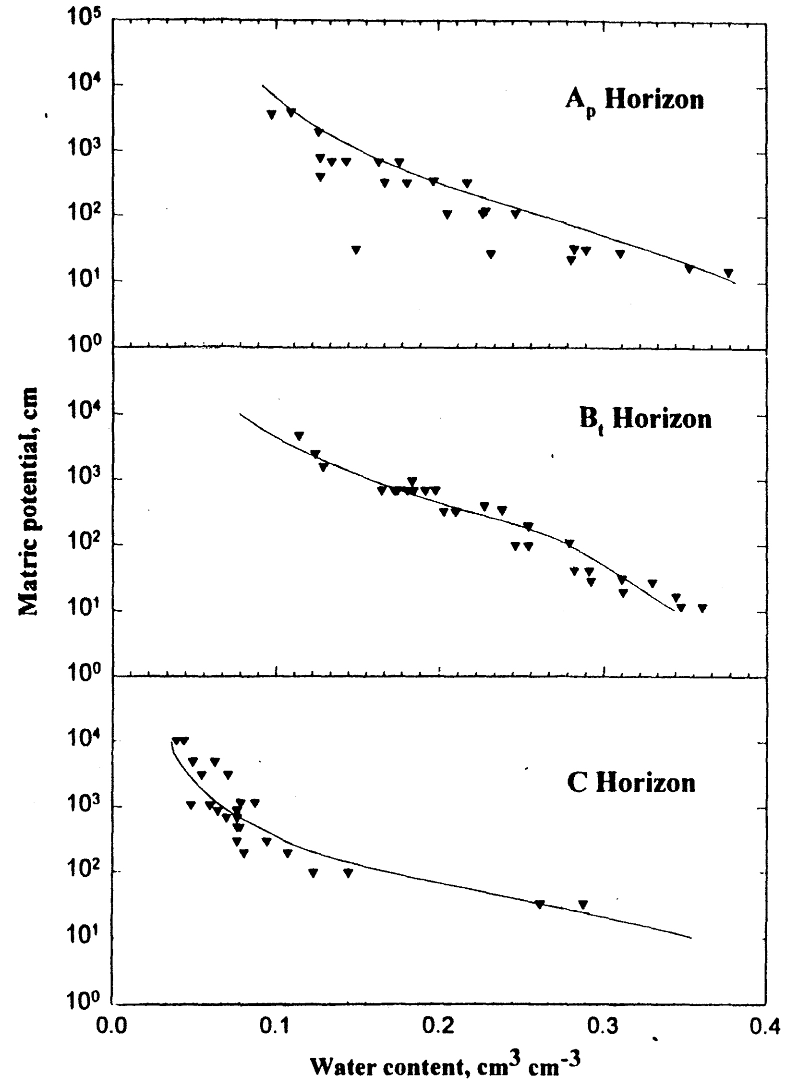

Figure 4-4. Water retention curves for the A_p, B_t and C horizons of Verndale sandy loam at Staples, MN. Retention curves wére fitted with the RETention Curve (RETC) program (van Genuchten et al., 1991).

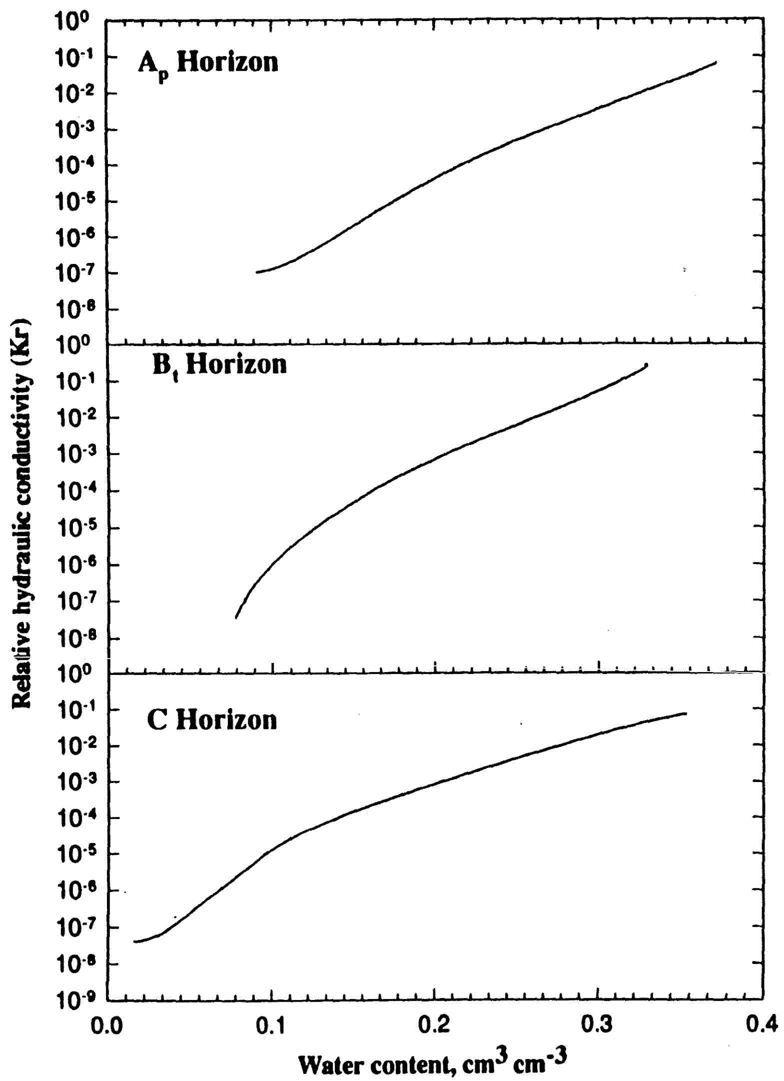

Figure 4-5. Relative hydraulic conductivities for the A_p, B_t and C horizons of Verndale sandy loam at Staples, MN. Kr curves were fitted with RETC program (van Genuchten et al., 1991).

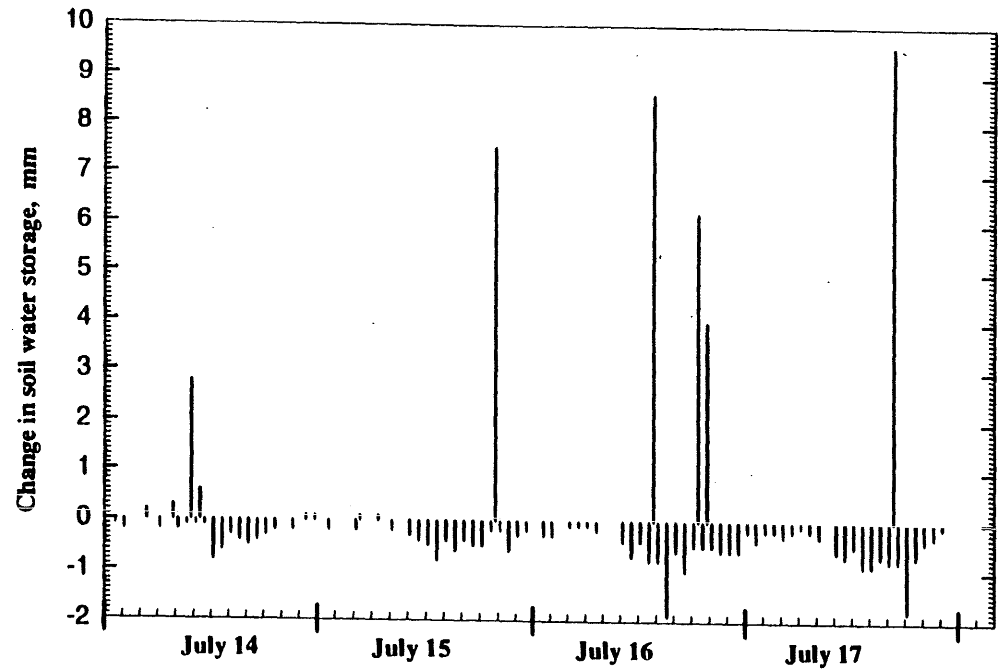

Figure 4-7. Change in hourly soil water storage under a potato plant at a drip irrigation plot.

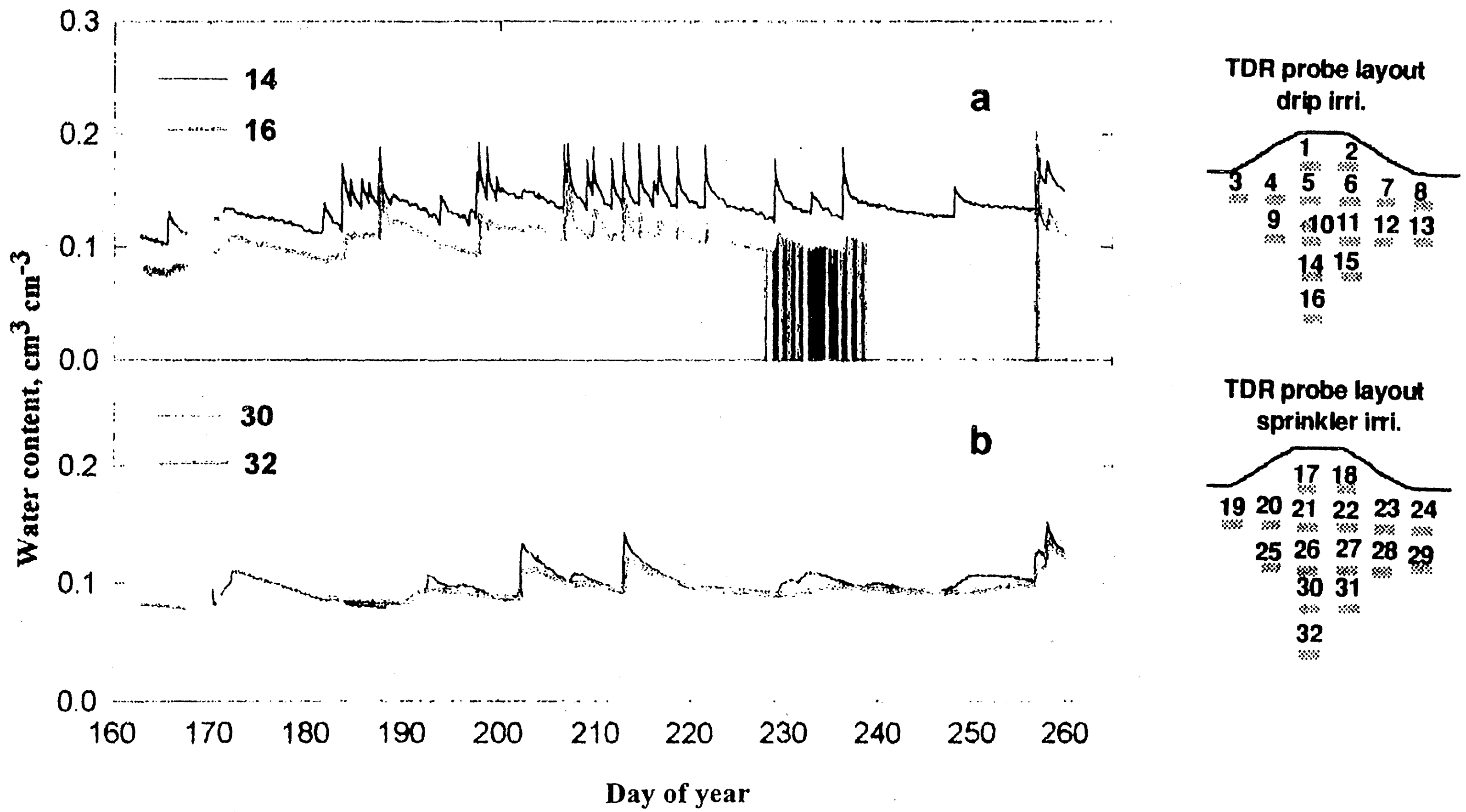

Figure 4-6. Variation in soil water content as a function of time under a growing potato plant in a) drip and b) sprinkler irrigated Verndale sandy loam. The numbers in the legend refer to the probe positions in the TDR probe layout diagram.

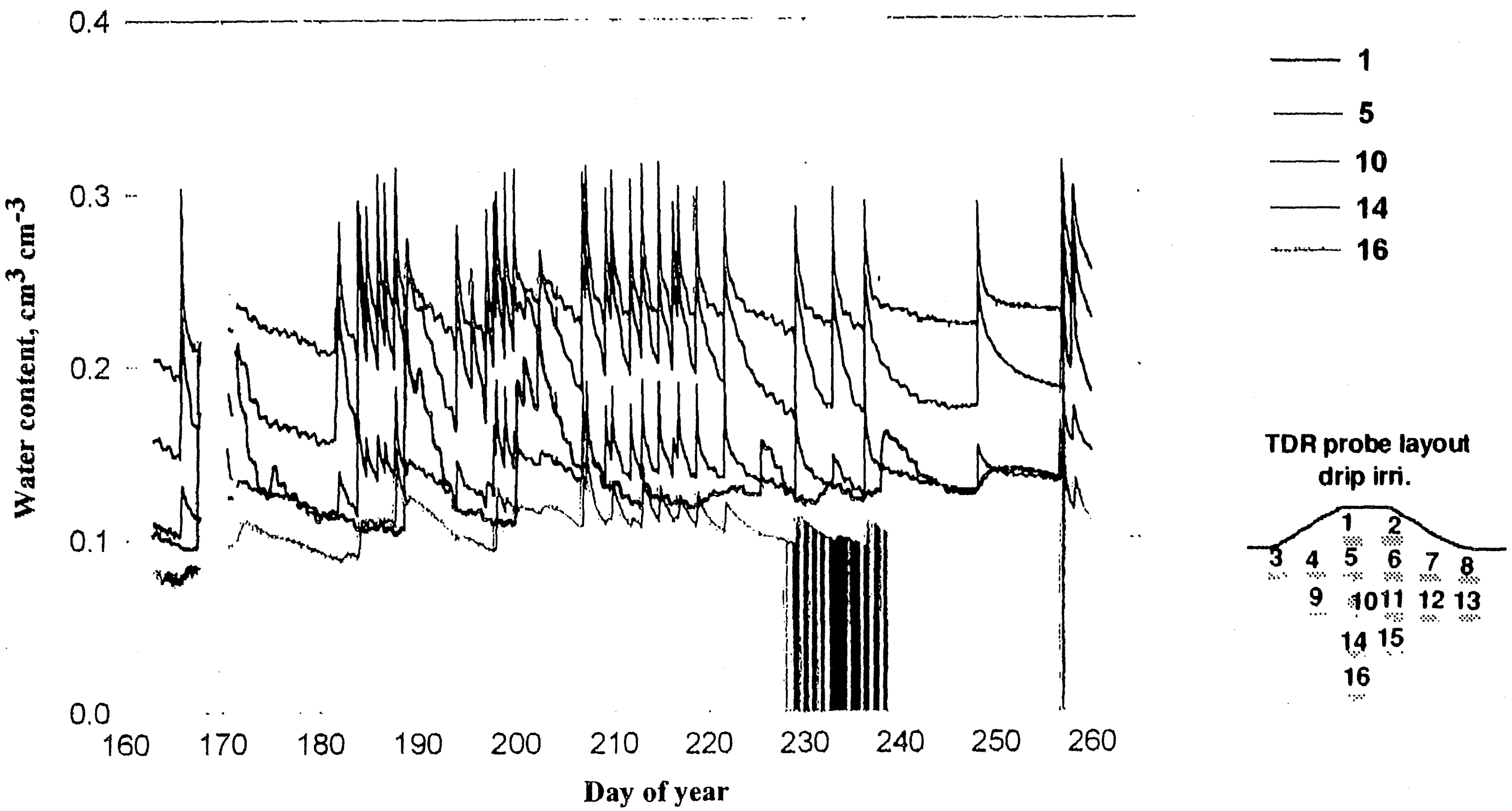

Figure 4-8. Variation in soil water content as a function of time under a growing potato plant in drip irrigated Verndale sandy loam. The numbers in the legend refer to the probe positions in the TDR probe layout diagram.

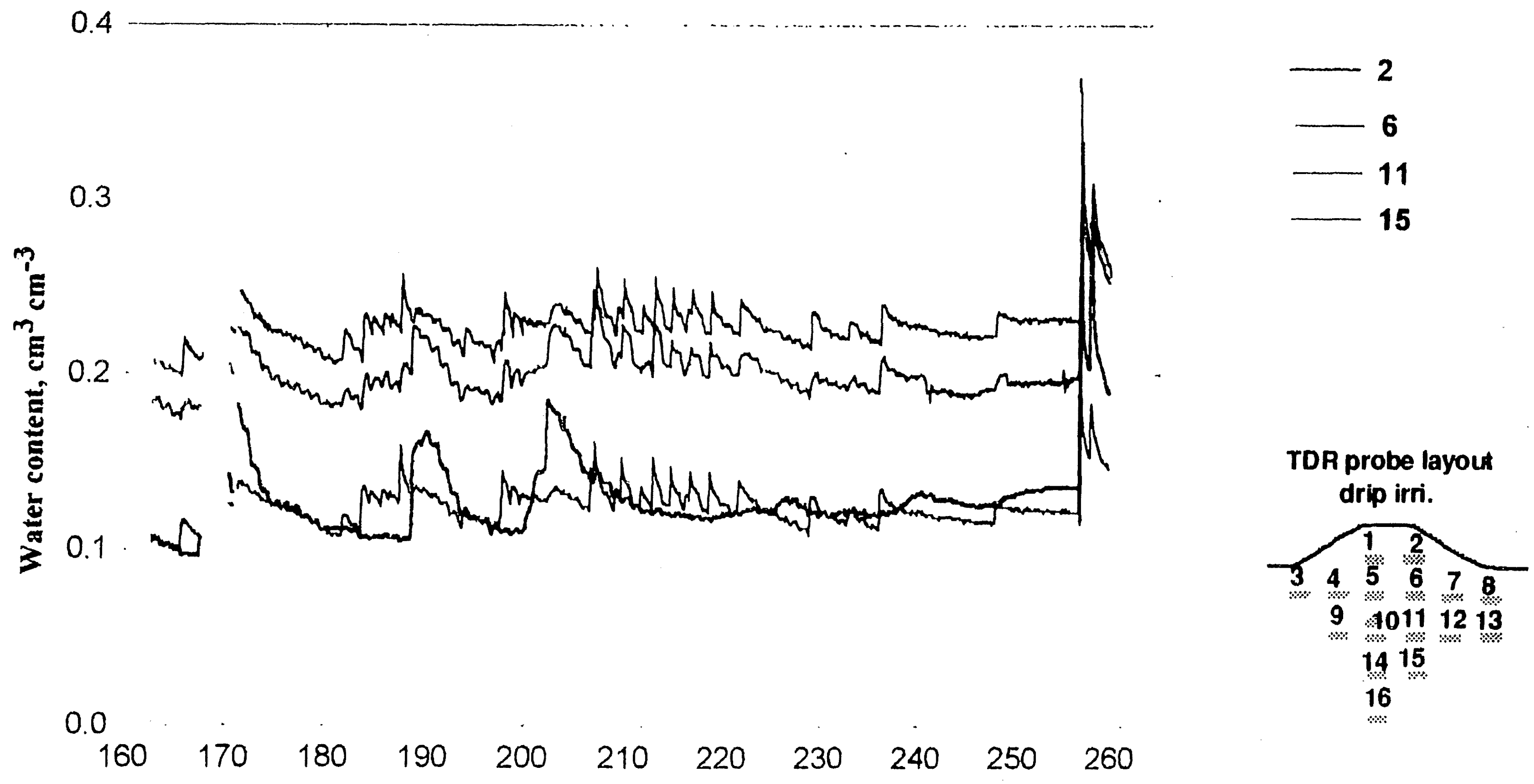

Figure 4-9. Variation in soil water content as a function of time under a growing potato plant in drip irrigated Verndale sandy loam. The numbers in the legend refer to the probe positions in the TDR probe layout diagram.

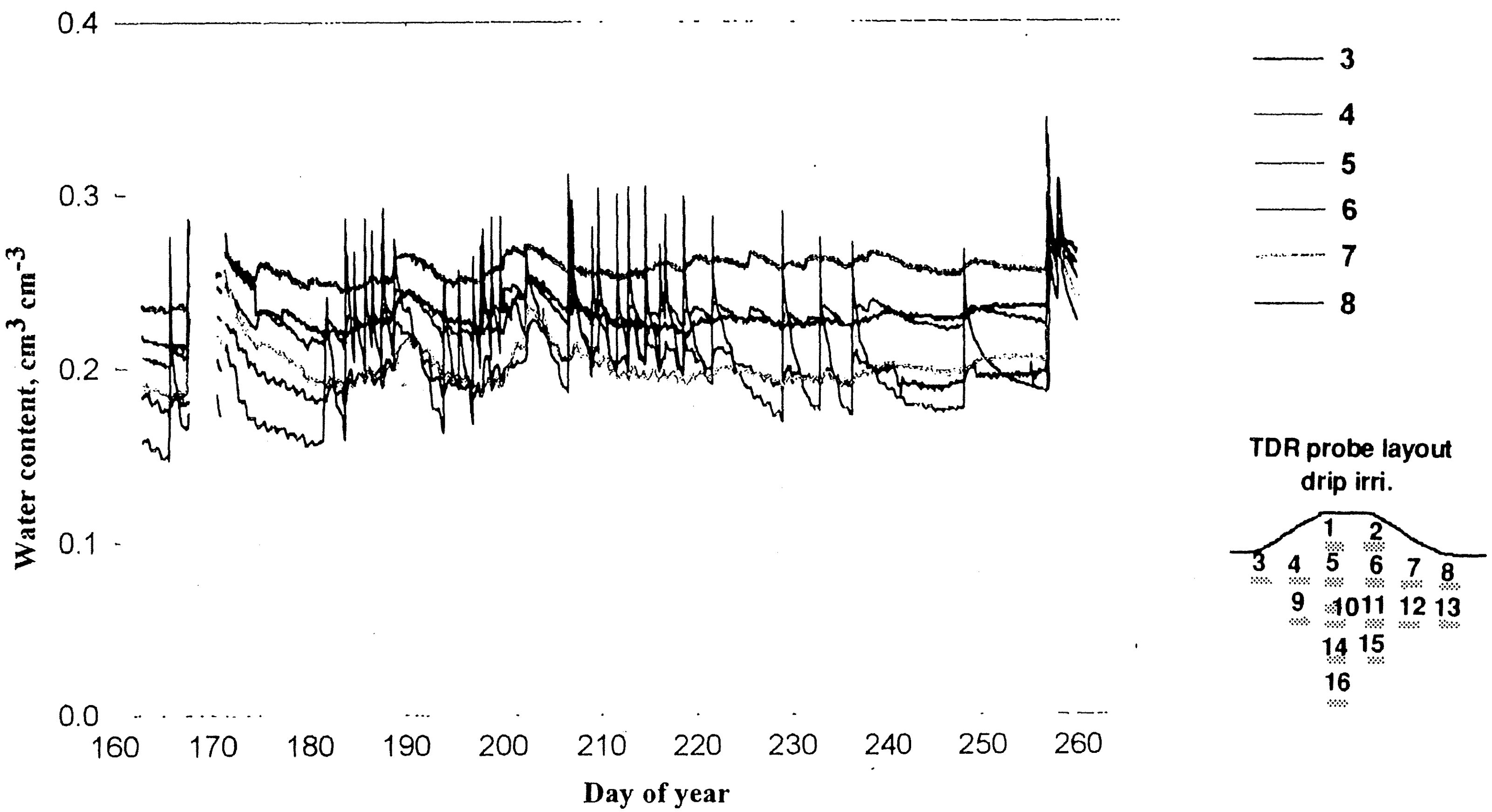

Figure 4-10. Variation in soil water content as a function of time under a growing potato plant in drip irrigated Verndale sandy loam. The numbers in the legend refer to the probe positions in the TDR probe layout diagram.

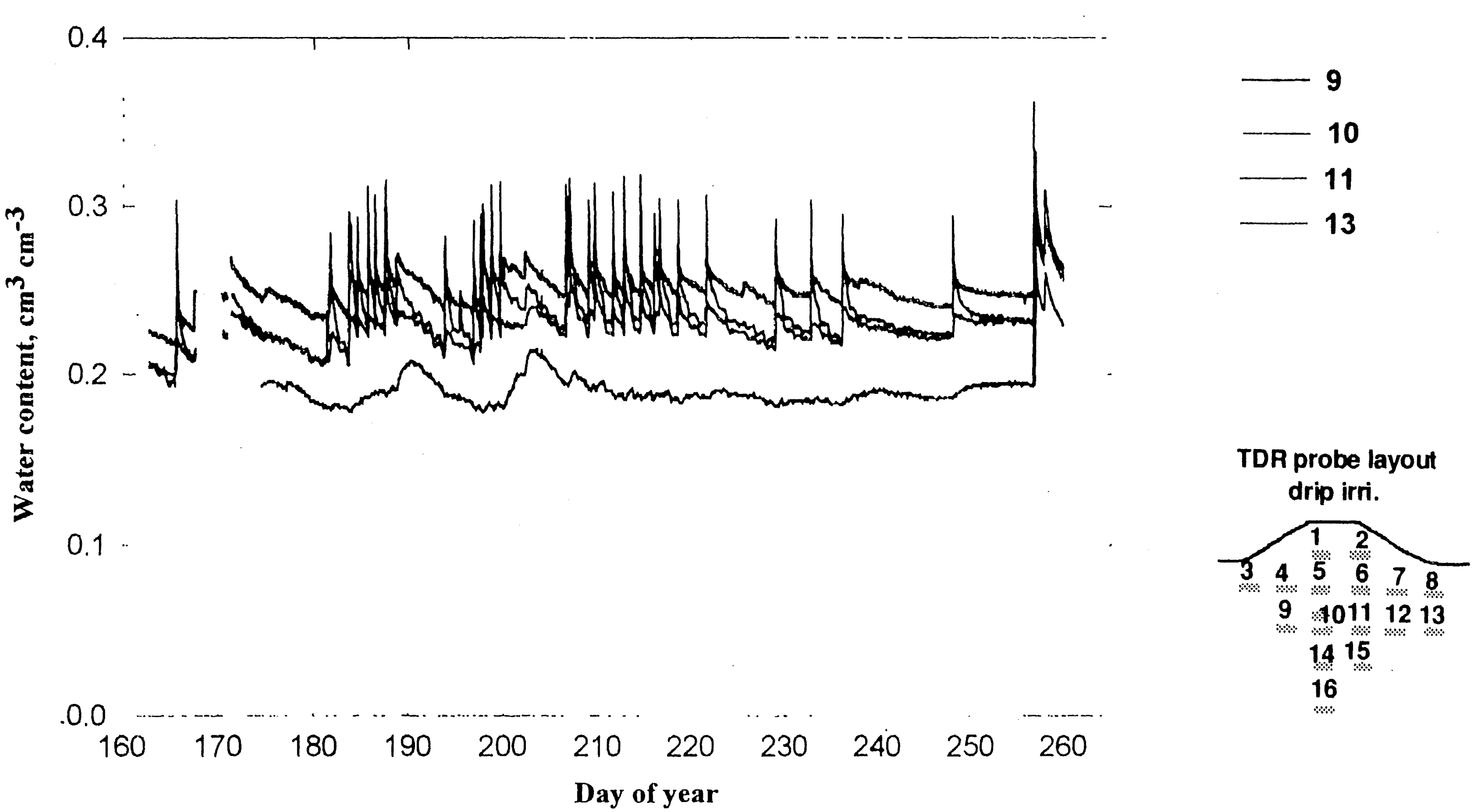

Figure 4-11. Variation in soil water content as a function of time under a growing potato plant in drip irrigated Verndale sandy loam. The numbers in the legend refer to the probe positions in the TDR probe layout diagram.

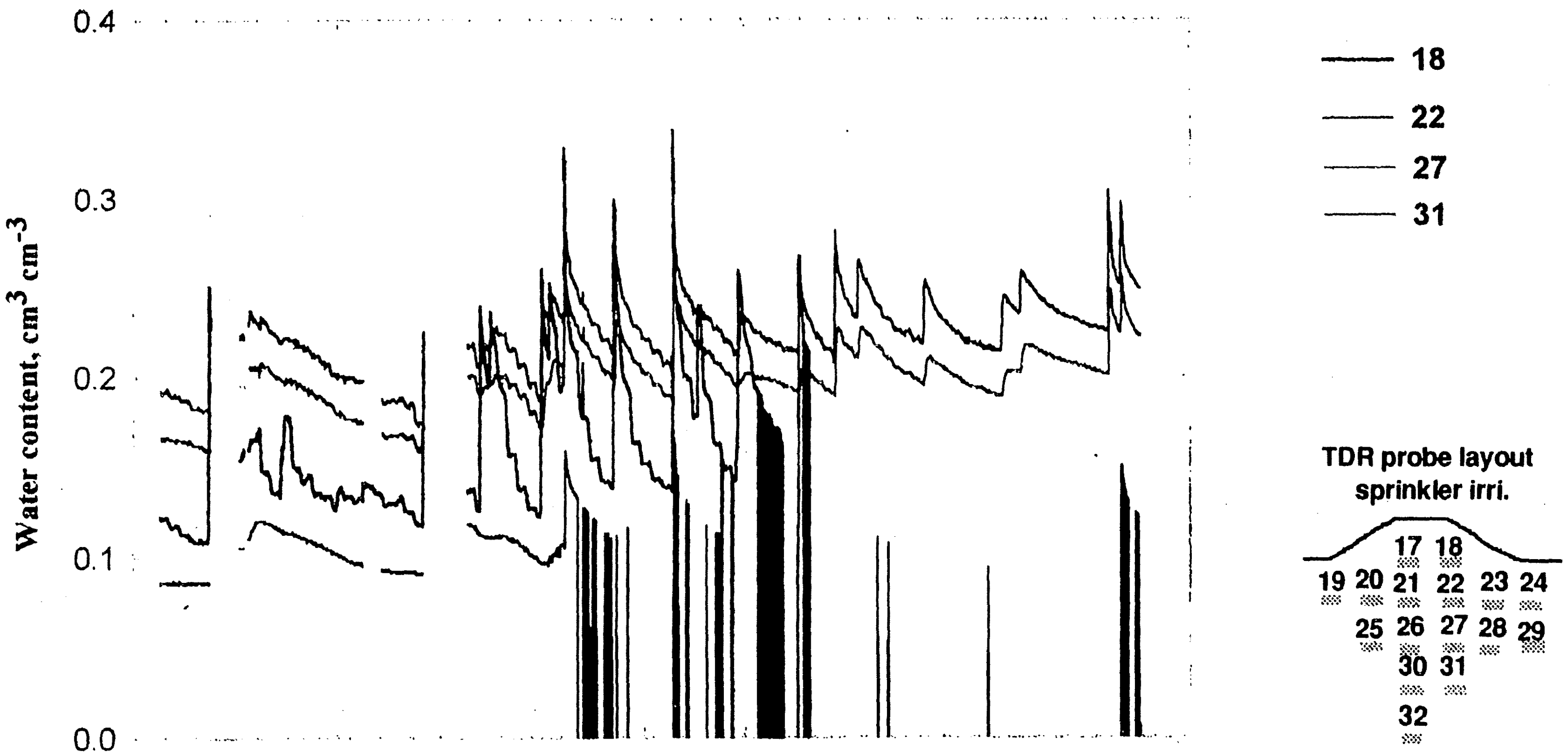

Figure 4-12. Variation in soil water content as a function of time under a growing potato plant in sprinkler irrigated Verndale sandy loam. The numbers in the legend refer to the probe positions in the TDR probe layout diagram.

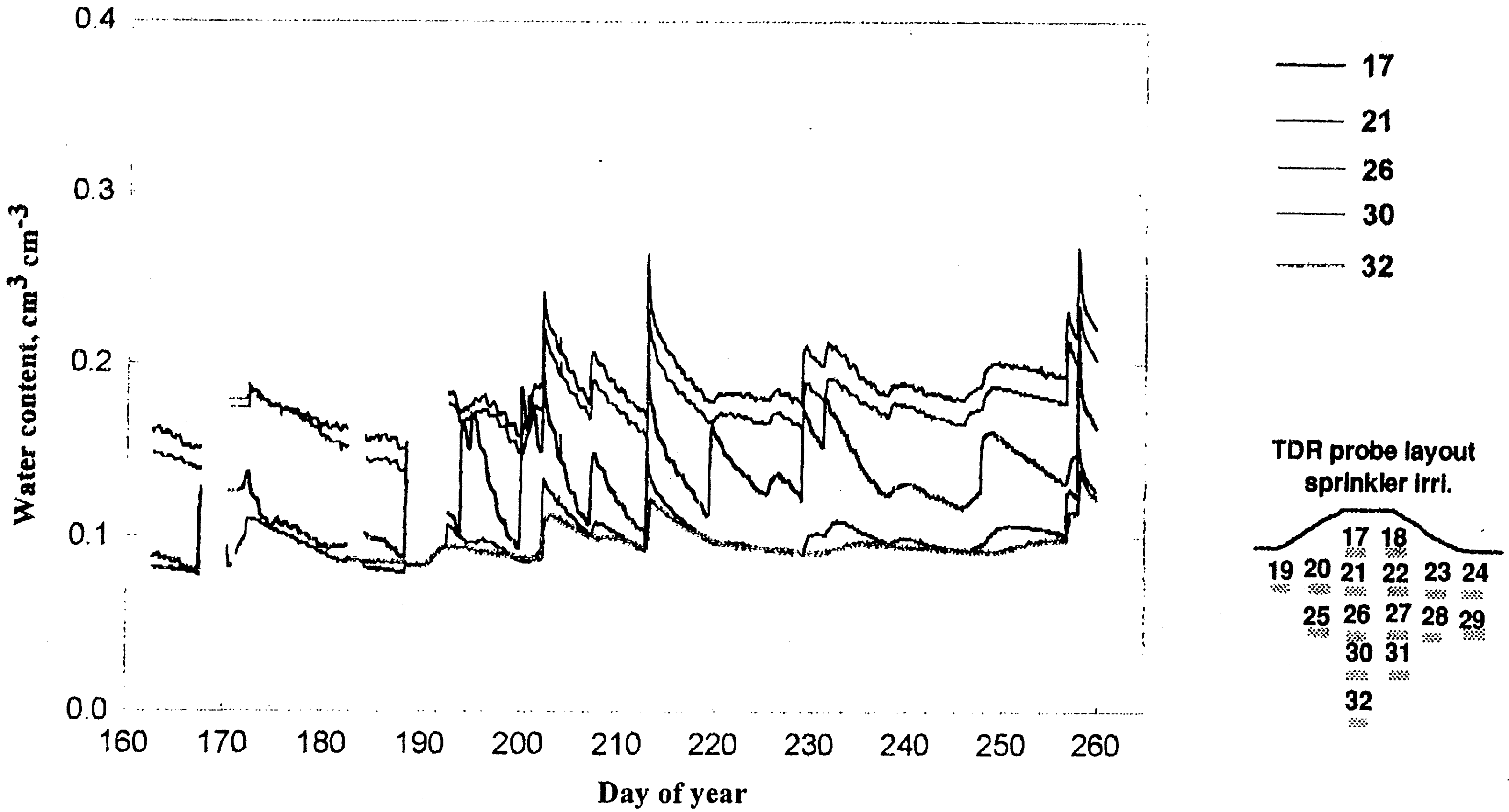

Figure 4-13. Variation in soil water content as a function of time under a growing potato plant in sprinkler irrigated Verndale sandy loam. The numbers in the legend refer to the probe positions in the TDR probe layout diagram.

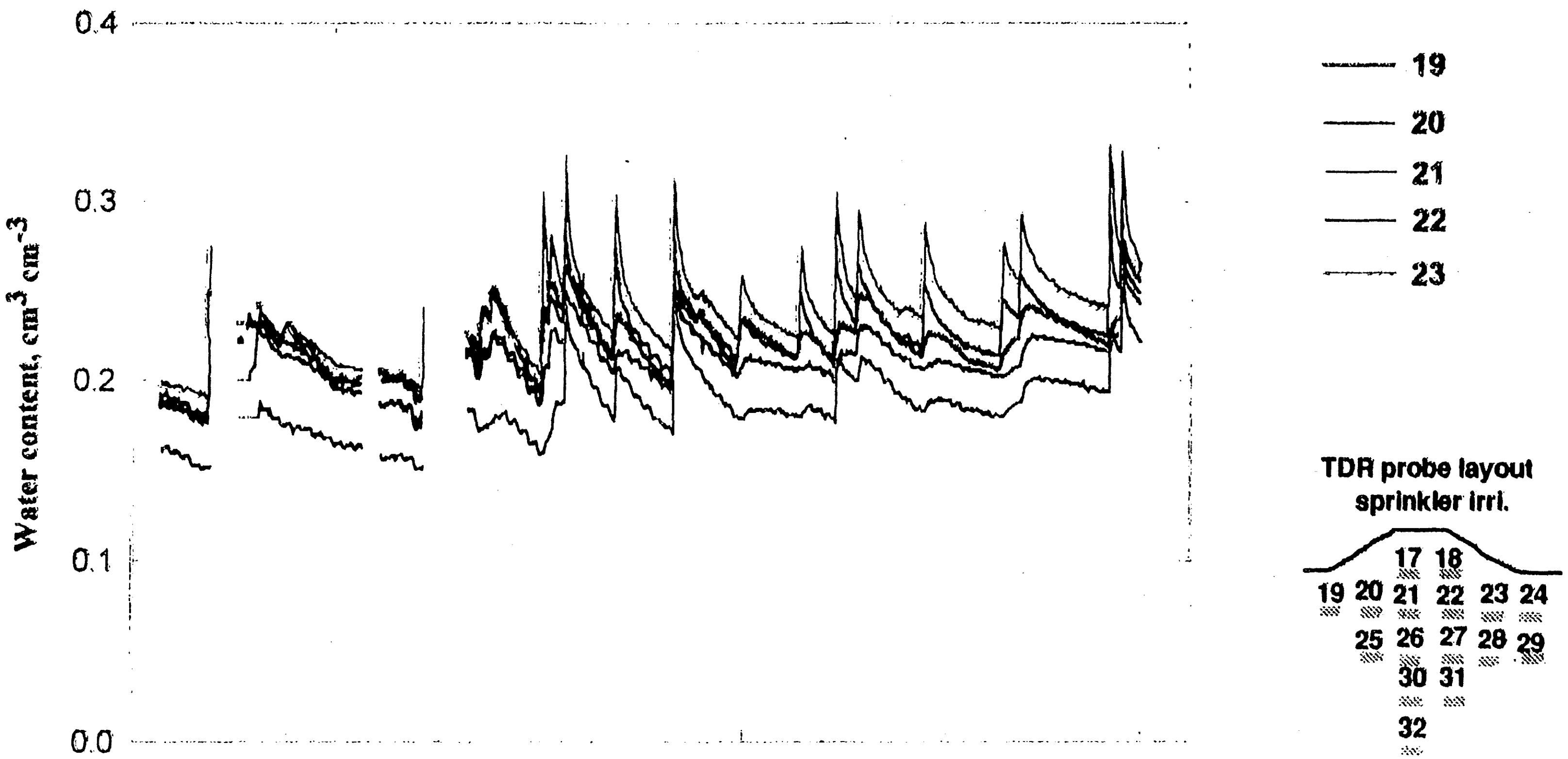

Figure 4-14. Variation in soil water content as a function of time under a growing potato plant in sprinkler irrigated Verndale sandy loam. The numbers in the legend refer to the probe positions in the TDR probe layout diagram.

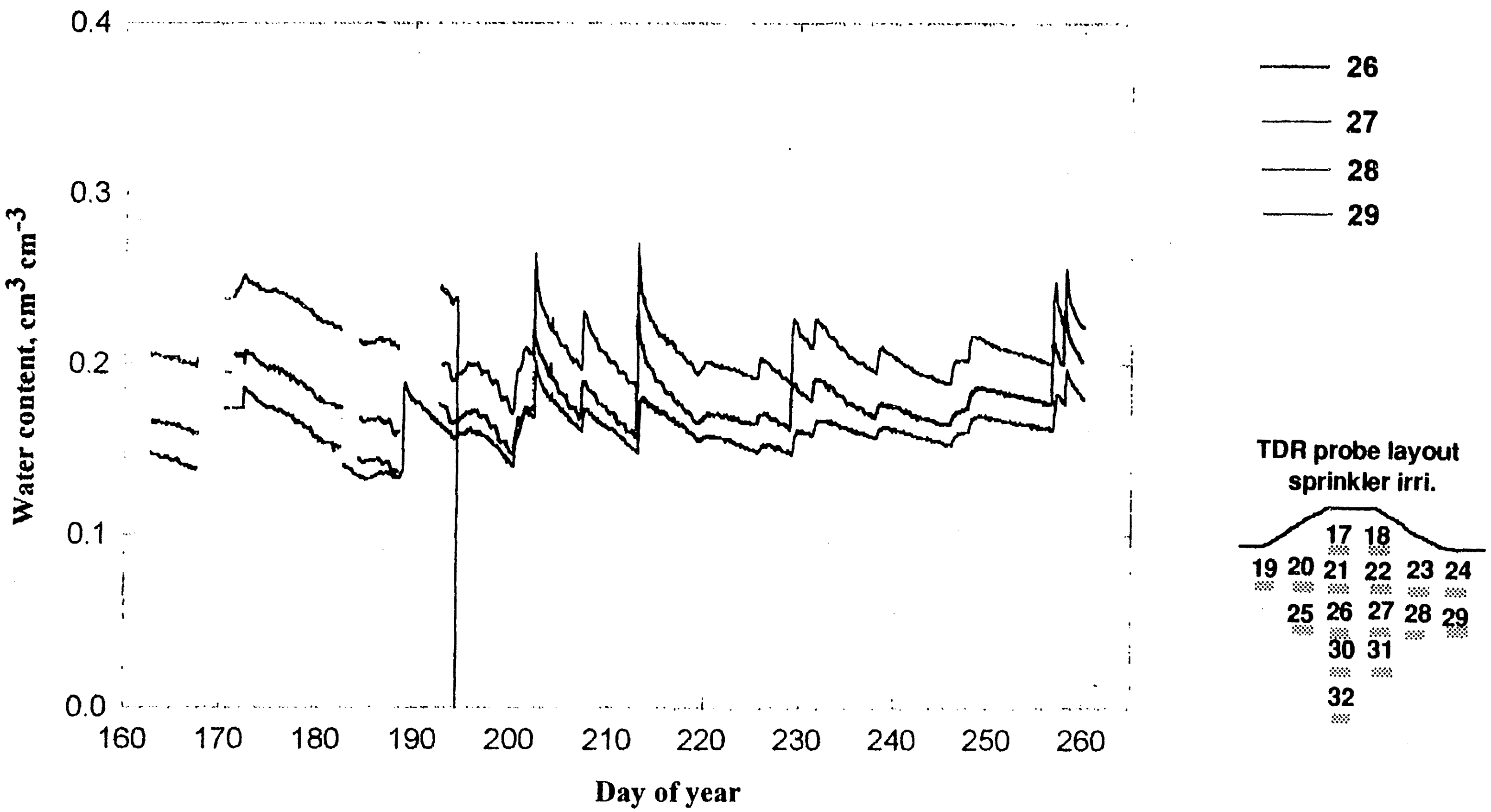

Figure 4-15. Variation in soil water content as a function of time under a growing potato plant in sprinkler irrigated Verndale sandy loam. The numbers in the legend refer to the probe positions in the TDR probe layout diagram.

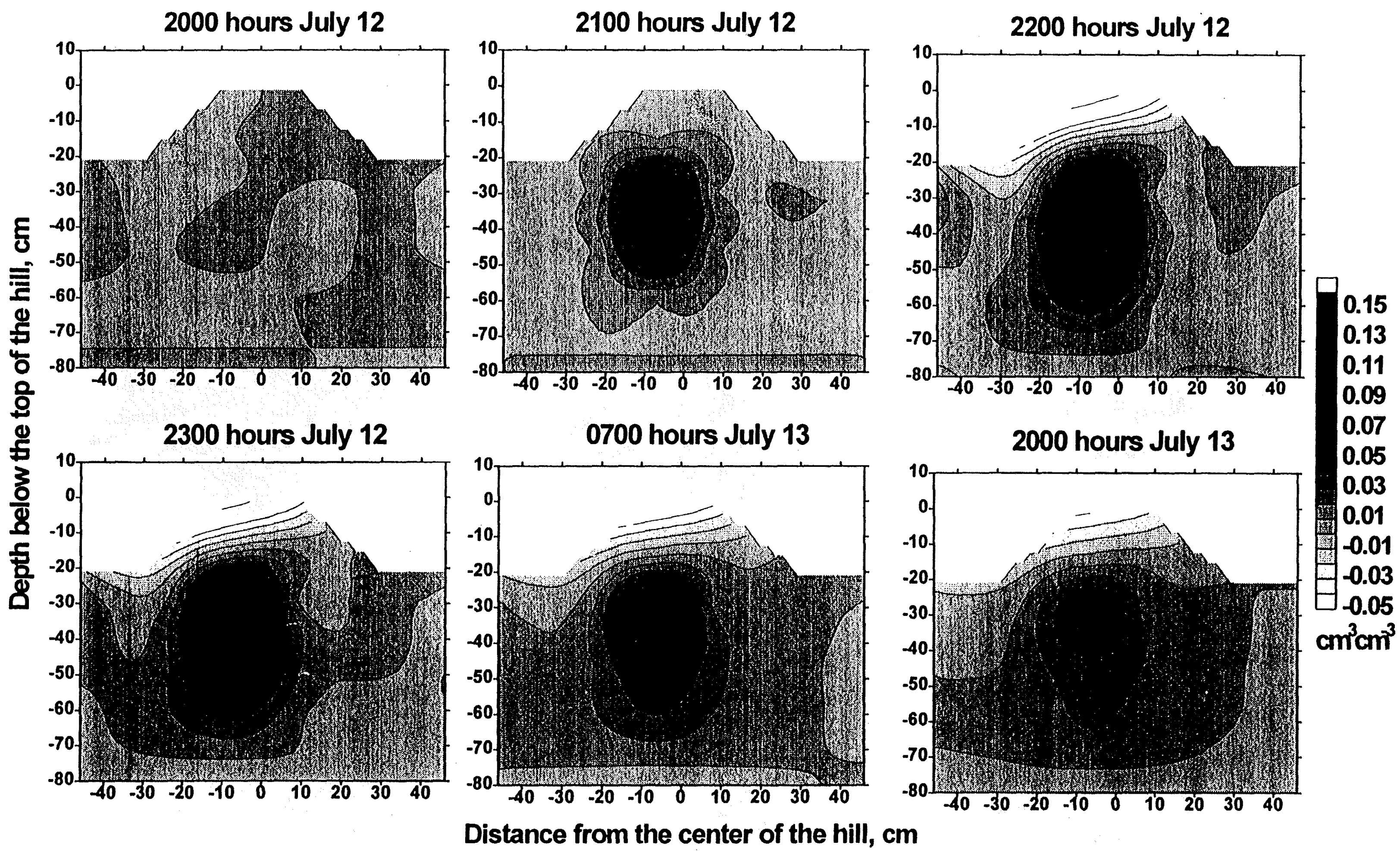

Figure 4-16. Changes in wetting pattern after 4 mm of water application by drip irrigation at 2000 hours on July 12, 1994. Wetting pattern is defined as an increase in water content relative to an initial condition. In this example, the initial condition corresponds to water content at 1900 hours on July 12, 1994.

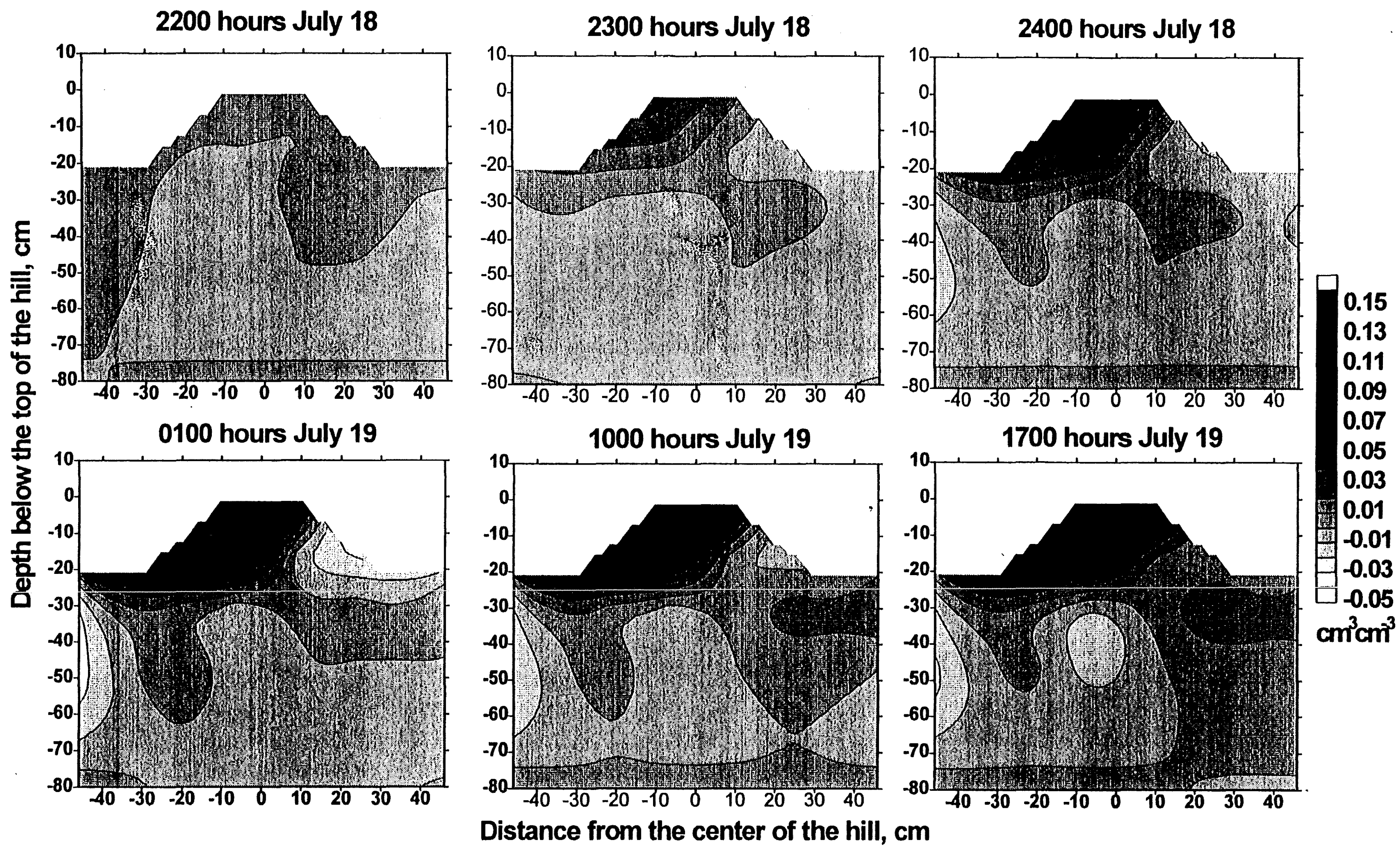

Figure 4-17. Changes in wetting pattern after a 16 mm of rain at drip irrigated plot at 2200 hours on July 18, 1994. Wetting pattern is defined as an increase in water content relative to an initial condition. In this example, the initial condition corresponds to water content at 2100 hours on July 18, 1994.

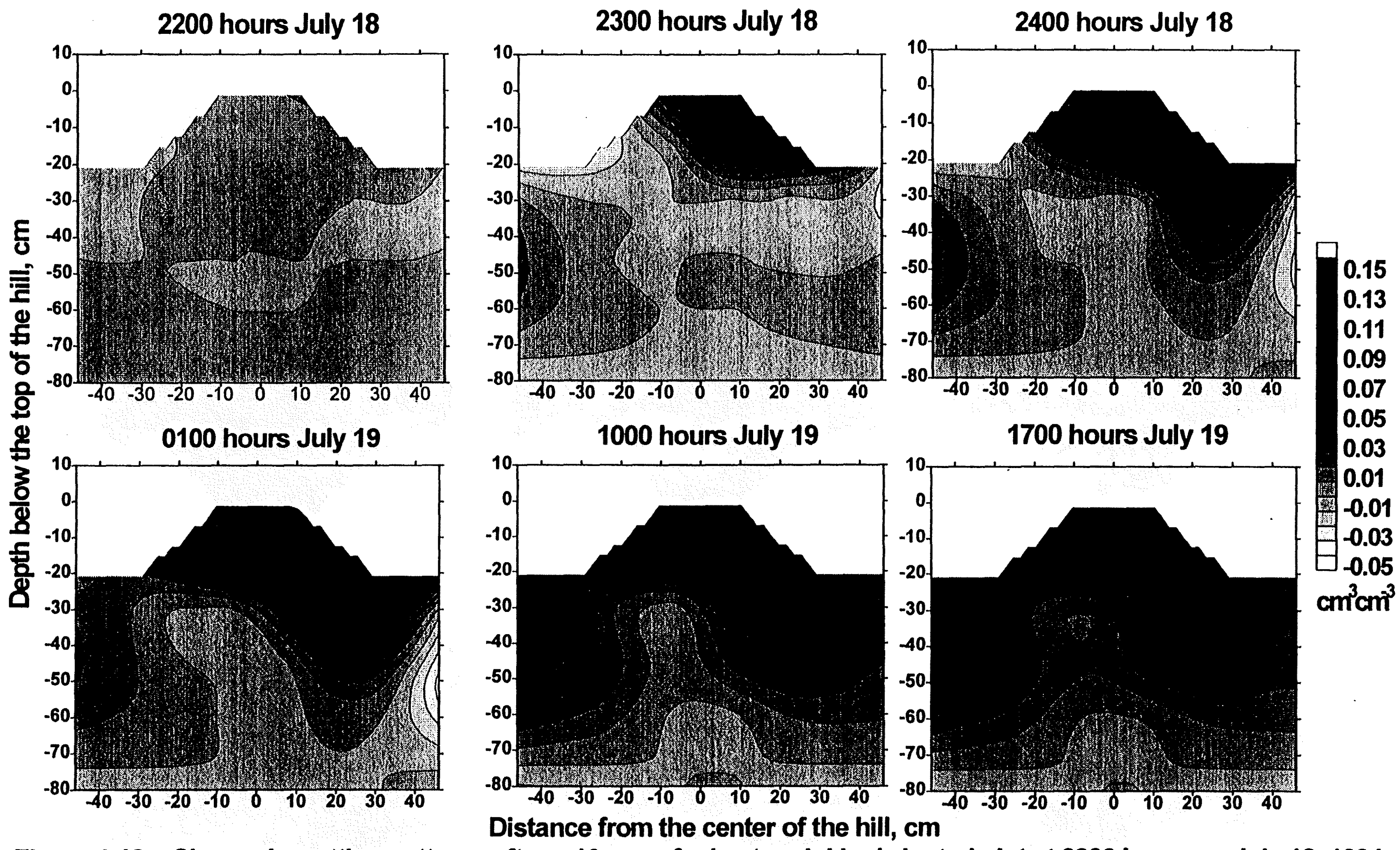

Figure 4-18. Change in wetting patterns after a 16 mm of rain at sprinkler irrigated plot at 2200 hours on July 18, 1994. Wetting pattern is defined as an increase in water content relative to an initial condition. In this example, the initial condition corresponds to water content at 2100 hours on July 18, 1994.

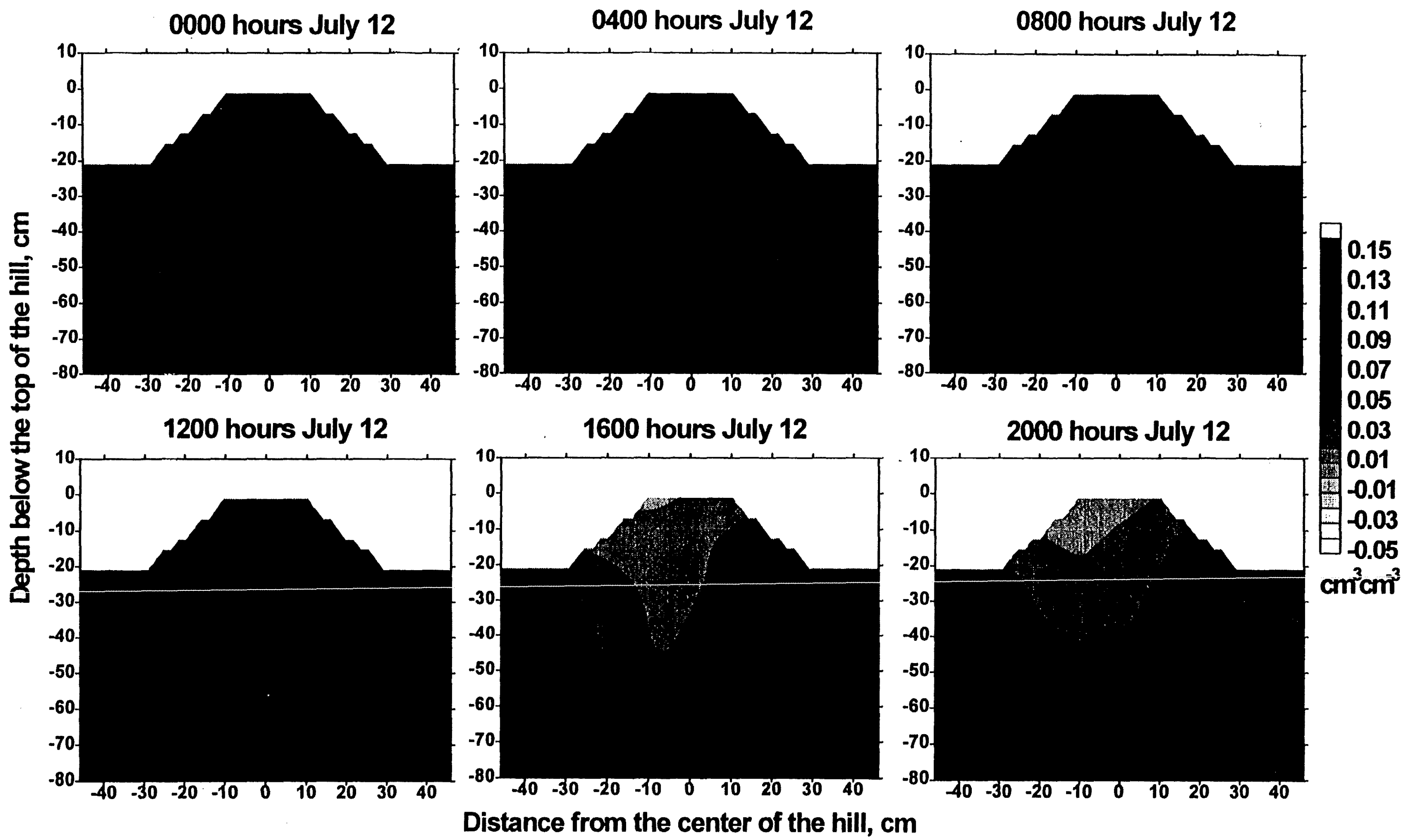

Figure 4-19. Changes in drying pattern from a drip irrigated plot on July 12, 1994. Drying pattern is defined as a decrease in water content relative to an initial condition. In this example, the initial condition corresponds to water content at 2300 hours on July 11, 1994.

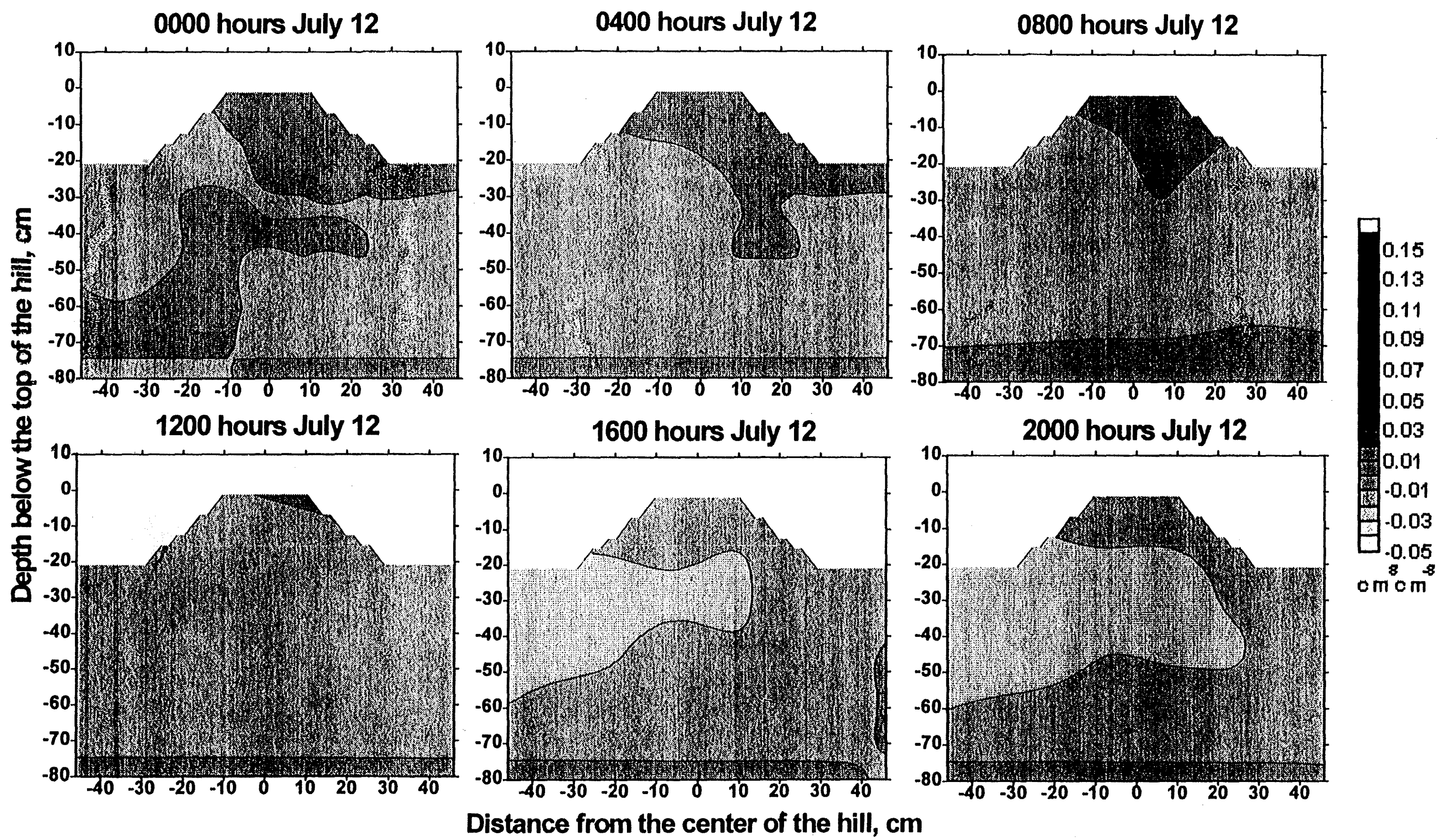

Figure 4-20. Changes in drying pattern from a sprinkler irrigated plot on July 12, 1994. Drying pattern is defined as a decrease in water content relative to an initial condition. In this example, the initial condition corresponds to water content at 2300 hours on July 11, 1994.

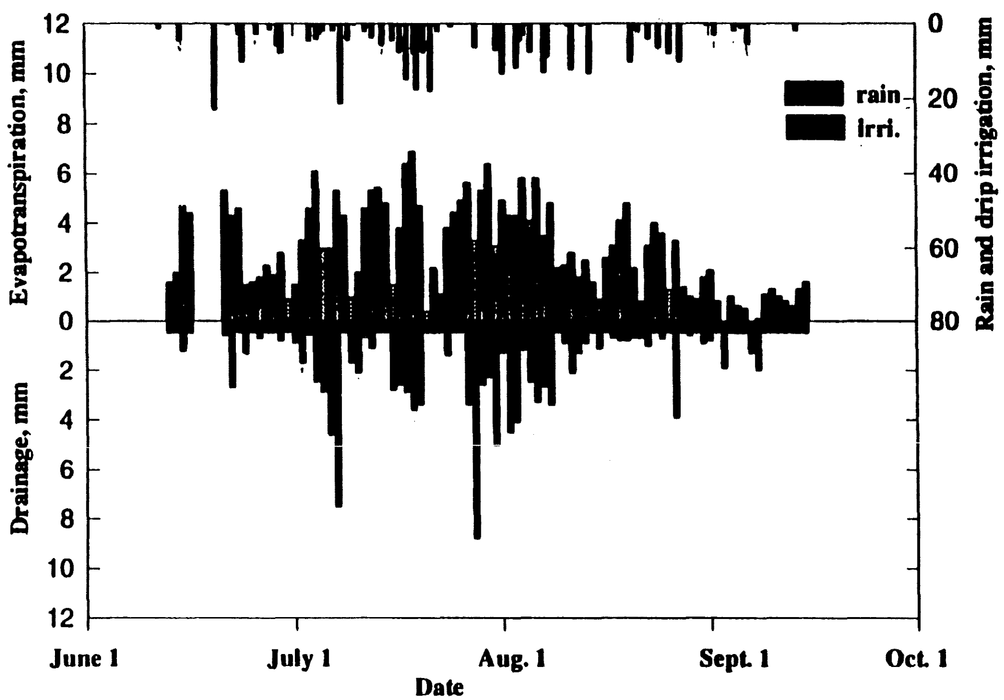

Figure 4-21. Daily precipitation, irrigation, evapotranspiration (ET), and drainage as a function of time for drip irrigated Verndale sandy loam soil at Staples, MN. ET and drainage were calculated based on the TDR water content maesurements.

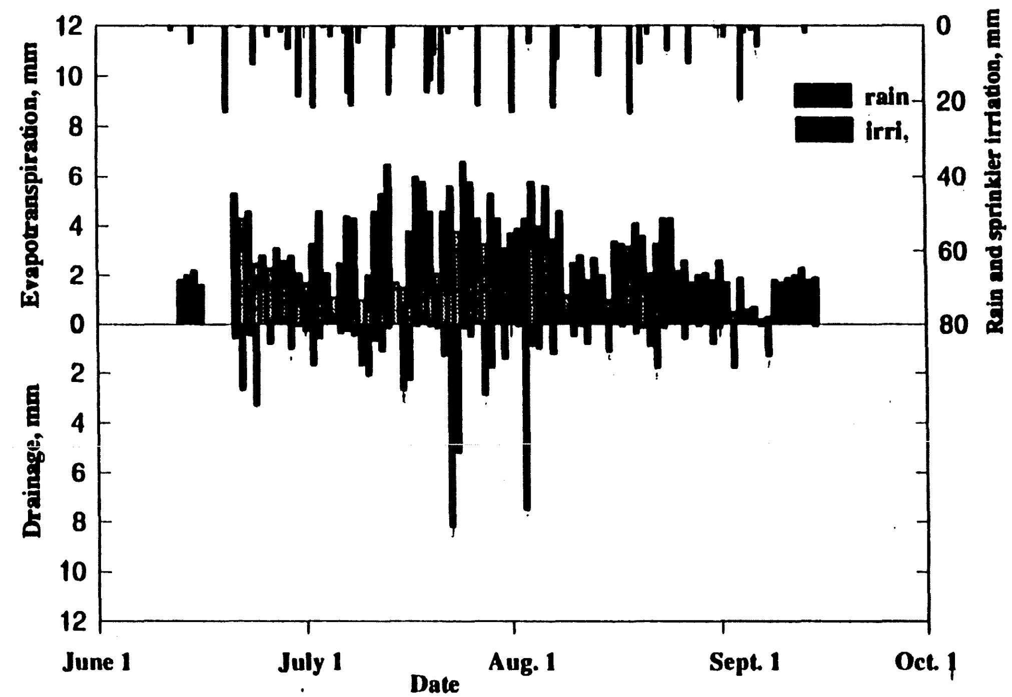

Figure 4-22. Daily precipitation, irrigation, evapotranspiration (ET), and drainage as a function of time for sprinkler irrigated Verndale sandy loam soil at Staples, MN. ET and drainage were calculated based on the TDR water content measurements.

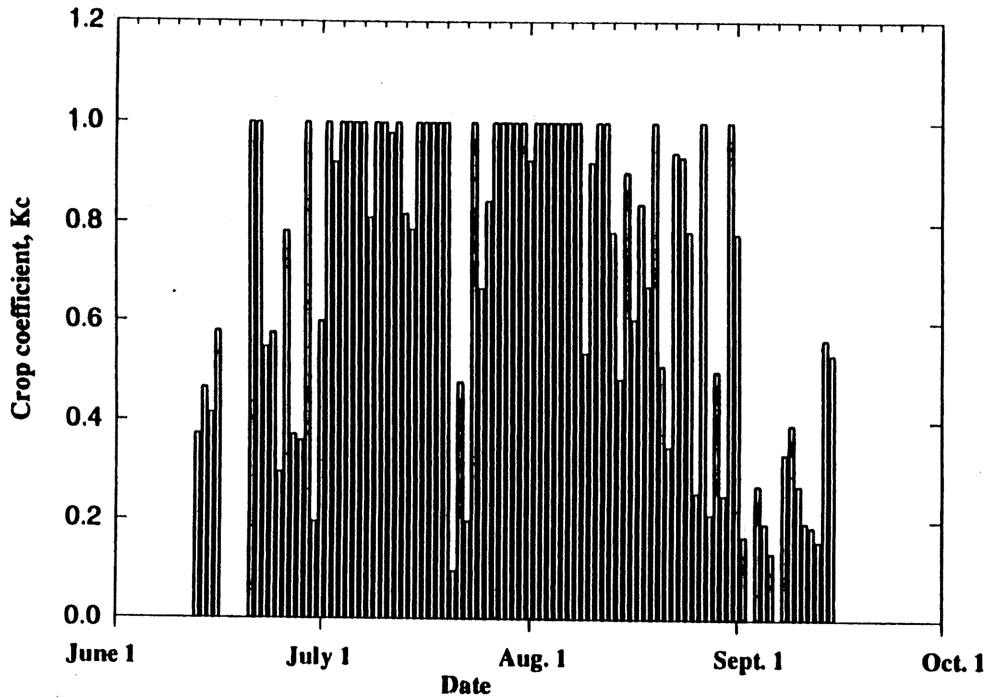

Figure 4-23. Ratio of the daily evapotranspiration to the potential evapotranspiration (crop coefficient, Kc) for potatoes as a function of time for drip irrigated Verndale sandy loam soil at Staples, MN.

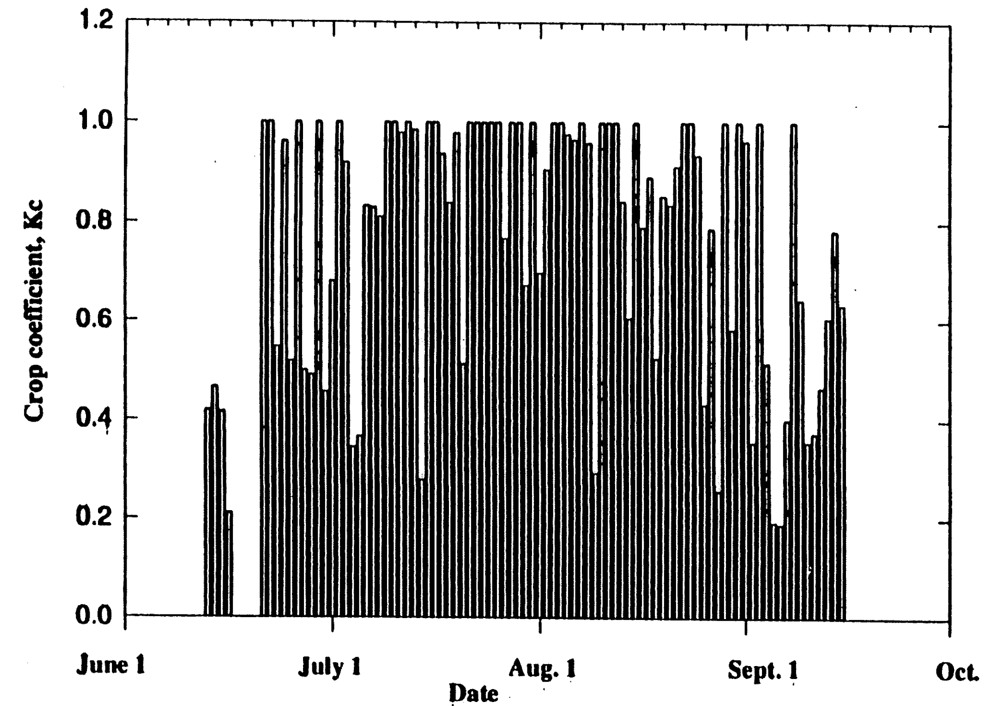

Figure 4-24. Ratio of the daily evapotranspiration to the potential evapotranspiration (crop coefficient, Kc) for potatoes as a function of time for sprinkler irrigated Verndale sandy loam soil at Staples, MN.

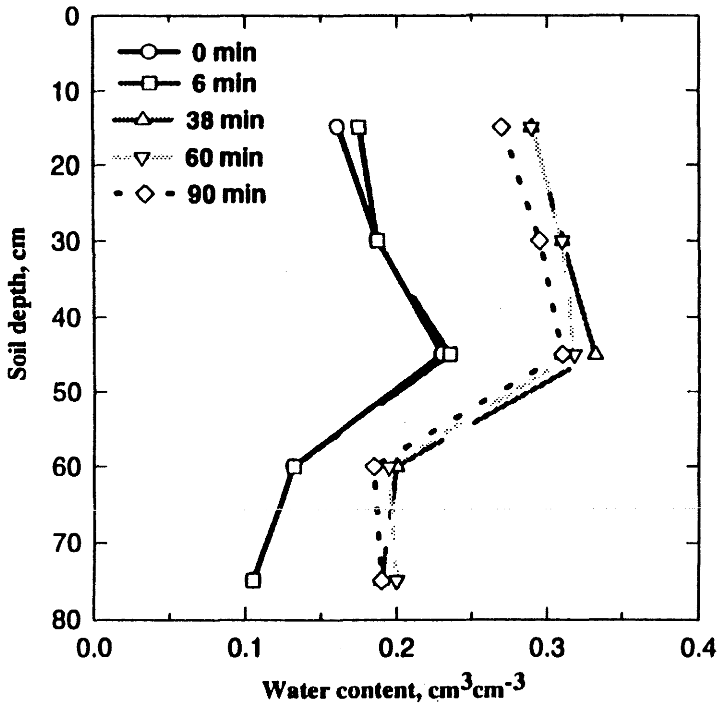

Figure 4-25. Changes in water content with soil depth since the start of an infiltration experiment where 20 cm of KBr was added at the soil surface over a period of 40 minutes. These data were gathered at the drip irrigated plot.

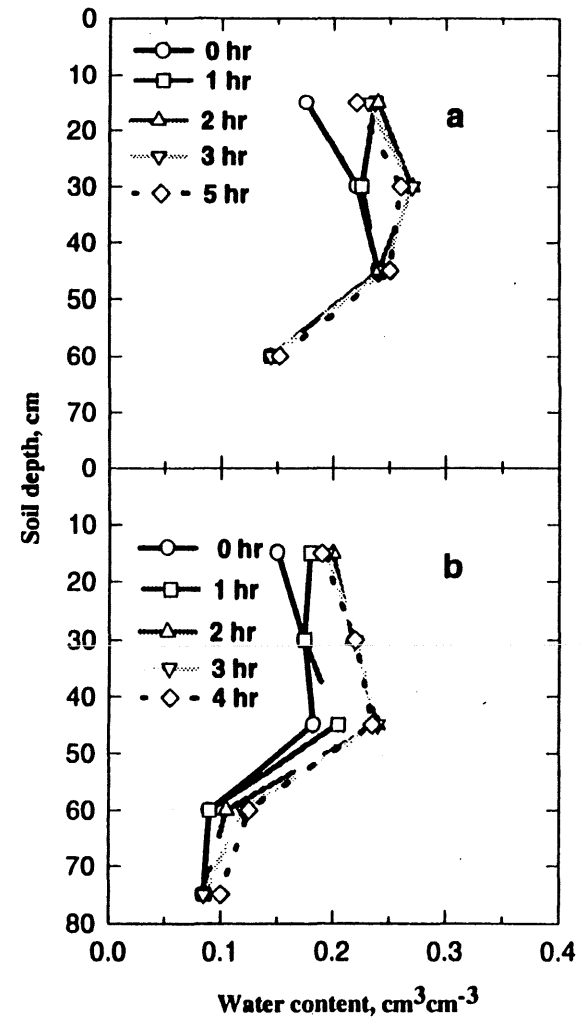

Figure 4-26. Changes in water contents with soil depth a) for the drip irrigated plot during a rain event of 1.42 cm in three hours, and b) for the sprinkler irrigated plot during 1.5 cm of sprinkler irrigation in one hour.

Chapter 5. NUMERICAL SIMULATION OF WATER MOVEMENT IN A RIDGE-FURROW SYSTEM WITH GROWING POTATO PLANTS

ABSTRACT

Our earlier experimental studies suggested that water movement under a ridge-furrow system used in potato production is a two dimensional problem. Since the experimental characterization of water movement under a ridge-furrow system for a whole range of treatments is expensive and time consuming, in this chapter, we discuss the use of a mechanistic 2-D model (SWMS_2D) to evaluate the role of stem flow, and the depth of drip tube placement on percolation losses with the subsurface drip vs. sprinkler irrigation.

In this study, we chose the SWMS_2D model for (1) its capability to handle the irregular soil surface configuration, and (2) its simplicity to simulate irrigation with a subsurface drip. After field testing of the model, we also ran sensitivity analysis of the model to (1) identify the optimal placement of drip line with respect to the ridge, (2) evaluate the role of potato plant canopy architecture (stem flow) on preferential flow, and (3) the effect of ridge-furrow surface configuration on soil wetting and drying patterns. Using this model, we also quantified the differences in percolation losses between the sprinkler and drip irrigations plots with ridge-furrow system at the soil surface.

Simulation results showed that there was not much water movement toward the surface of the ridge when a drip was installed at 40 cm or deeper depth from the top of the ridge in Verndale sandy loam. This suggests that the application of mobile nutrients such as nitrate through the drip line in this soil will be of limited benefit because the potato roots are not fully developed at the early stage of potato growth, and to take up fertilizer from deeper depth. For conditions, where drip irrigation does not wet up the soil surface, banded application of starter fertilizer near the row will be a better strategy than the application through the drip line. Comparison of simulation results from sprinkler and drip irrigation showed that drip irrigation could reduce water percolation losses compared to the sprinkler irrigation especially in locations where rains often occur right after irrigation.

INTRODUCTION

Degradation of groundwater quality is becoming an ever increasing concern of the general public. A major reason for this concern is an increased concentration of nitrate in groundwater and its implication with respect to "Blue Baby" syndrome. In Minnesota, the survey by Klaseus et al. (1988) found elevated nitrate in 43% of the 500 wells tested in 51 counties. A significant number of these contaminated wells were in glacial outwash soils of Central Minnesota. A USGS study (Myette, 1984) of 124 wells in Hubbard, Morrison, Otter Tail and Wadena counties of Central Minnesota showed that nitrate concentration has been continuously increasing since the 1960's. In some wells, concentration of nitrate have exceeded the EPA drinking water standards of 10 mg l^{-1}. Degradation of shallow aquifer ground water in outwash soils of Central Minnesota is associated with intensive farming (Myette, 1984). Because of their low water holding capacity and rapid drainage, these soils present an increased risk of nitrate leaching to shallow groundwater. Potato is one of two major crops grown in these soils. Since potato plants have a relatively shallow root system (small root length per unit land area), these plants are sensitive to water stress (Gregory and Simmonds, 1992). As a result, potatoes are frequently irrigated especially in sandy outwash soils. In addition, potatoes are often excessively fertilized to insure maximum yield and high quality.

Our previous studies showed that under the best irrigation schedule, rain alone or in combination with irrigation was the major cause of excessive water percolation and nitrate leaching past the root zone in Minnesota outwash soils. Therefore we concluded that in order to minimize this leaching, it was essential that some soil storage remain unfilled after irrigation in order to capture unforeseen rain. Other than deficit irrigation, one way to leave unfilled pore space in soil after irrigation is through the use of surface or subsurface drip irrigation. Because of the expense involved in laying and picking up surface drip lines, subsurface drip irrigation appears to be more promising for potato production. With subsurface drip irrigation, water can be easily applied to concentrated roots. This in turn leaves a significant soil storage outside the root zone where water from unforeseen rains that may occur right after irrigation can be stored. Depth of a drip line relative to the ridge is a key factor in maximizing the availability of irrigation water to plant, in reducing nitrate leaching from irrigation, and in increasing the capacity of soil to capture water from unforeseen rains. Since potatoes are grown in a ridge-furrow system, one must also consider the impact of variable water flux at the soil surface (Saffigna et al., 1976; Timlin et al., 1992) on nitrate leaching under both sprinkler and drip irrigation systems.

In 1994, we conducted a field experiment to quantify the wetting and drying patterns of a Minnesota outwash soil under both sprinkler and drip irrigation systems with a growing potato plant. Wetting and drying patterns were monitored with Time Domain Reflectometry (TDR) probes installed at various depths under the ridge-furrow system. As expected, results showed that water movement under a ridge-furrow system with a growing potato plant is a two dimensional problem. Since the experimental characterization of water movement under a ridge-furrow system is relatively expensive, time consuming, and can also be limited to a few treatments, we were interested in using a mechanistic 2-dimensional model to evaluate the impact of drip irrigation on water percolation for various drip placement scenarios relative to the sprinkler irrigation system.

Many studies have been done in the past on analytical and numerical solutions of the Richards' equation for two and three dimensional water flow from a surface trickle source. Bresler (1975) developed a finite difference numerical model for simulating two dimensional simultaneous transport of water and a non-interacting solute from a surface drip line in homogeneous sand and loam soils. Warrick (1985) analytically calculated the wetted surface from a surface drip irrigation source (wetted-disc and wetted strip). Healy and Warrick (1988) numerically estimated the time-variant extent of the wetting front and wetted volume resulting from a surface drip irrigation source. Mallawatantri (1994) used a two dimensional finite difference potato growth model developed by Annandale (1991) to quantify the effects of stem flow and hill runoff from rainfall and surface irrigation on nitrate leaching under both hill and furrow regions of potato beds. However, there is little research reported on the two dimensional water flow patterns from a subsurface drip irrigation.

A finite element model SWMS_2D (ver. 1.2) developed by the U.S. Salinity Laboratory (Simunek et al., 1994) is capable of simulating water movement in two-dimensional variably saturated media. The SWMS_2D model has been successfully used by Wu et al. (1995) to simulate water and solute transport to a suction lysimeter. Zhang (1994) used the CHAIN_2D model (Simunek et al., 1993) to simulate water distribution in soil both under flood and drip irrigation. The CHAIN_2D model has the same water flow sub-program as the SWMS_2D model. The difference between the two models is that the

CHAIN_2D model is capable of handling chemical transformations.

In this study, we used the SWMS_2D model to simulate water flow patterns under a ridge-furrow system for both sprinkler and subsurface drip irrigated soils. We selected the SWMS_2D model because of its capabilities to handle both the irregular soil surface configuration and its simplicity to simulate irrigation with subsurface drip. The specific objectives of our study were:

1. To test the capability of the SWMS_2D model to simulate measured wetting and drying patterns under both sprinkler and drip irrigation systems.

2. To quantify the role of stem flow (effect of plant canopy architecture) and the ridge-furrow surface configuration on soil wetting patterns and degree of percolation losses from the soil profile.

3. To quantify the effects of drip line placement relative to the top of the ridge on soil wetting patterns and degree of percolation losses from the soil profile.

4. To quantify the effects of sprinkler and subsurface drip irrigation on percolation losses from a ridge-furrow configured surface.

MATERIALS AND METHODS

THE SWMS_2D MODEL

A detailed description of the SWMS_2D model is given in Simunek et al. (1994). Briefly, the program numerically solves the Richards' water flow equation (Eq. [1]) for variably saturated flow media using the Galerkin linear finite element scheme.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}[K\,(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A})] - S \qquad [1]$$

where θ is the volumetric water content, $cm^3\,cm^{-3}$; h is the pressure head, cm; the S term accounts for water uptake by plant roots; x_i (i=1,2) are the spatial coordinates, cm; t is time, hour; K_{ij}^{A} are components of a dimensionless anisotropy tensor $\mathbf{K}^{A}$; and K is the unsaturated hydraulic conductivity function, $cm\,h^{-1}$ given by

$$K(h,x,z) = K_s(x,z)\;K_r(h,x,z) \qquad [2]$$

where K_r is the relative hydraulic conductivity and K_s is the saturated hydraulic conductivity, $cm\,h^{-1}$.

FLOW DOMAIN

Following the procedure of Simunek et al. (1994), we divided the flow regions into a network of quadrilateral elements where the corners of these elements are taken to be the nodal points. The dependent variable is the pressure head function h (x, z, t) which is approximated by h' (x, z, t) as follows:

$$h'(x, z, t) = \sum_{n=1}^{N} \phi_n(x, z) h_n(t) \qquad [3]$$

where ϕ_n are piecewise linear basis functions satisfying the condition $\phi_n(x_n, z_m)=\delta_{nm}$, δ_{nm} is the Kronecker delta having a value of 1 or 0 according to the condition specified, h_n are unknown coefficients representing the solution of Eq. [1] at the nodal points, and N is the total number of nodal points. Since the flow domain under a ridge-furrow system is symmetric around the z axis going through the center of the ridge (Figure 5-1), only the right hand side of the flow domain was simulated. The simulated results based on this half flow domain are then mirrored to the left hand side to get the complete flow pattern.

Grid net work for the right hand side of the flow domain used in the SWMS_2D model simulating a ridge-furrow system is shown in Figure 5-2. A drip was installed just above the Bt horizon (at 40 cm below the top of the ridge or 25 cm below the original soil surface). The water emitter occupied 3 nodes with a total width of 3 cm. Since the soil hydraulic properties at the boundaries such as at the water emitter, along the soil surface of the ridge-furrow configuration, and along the interface between the Bt and the C horizons change dramatically on water application, element size along these boundaries was kept small. Farther from these boundaries, the element size was increased in order to reduce the computation time. In total, there were 330 nodes and 291 quadrilateral elements in the flow domain (Figure 5-2). The SWMS_2D model automatically subdivided the quadrilaterals into triangles during the program executions.

INITIAL AND BOUNDARY CONDITIONS

Unless mentioned, simulations were run for 10 days starting on 0000 hour on July 12, 1994. The matric potential at 0000 hour on July 12 was set equal to -33 kPa (at field capacity) for the whole domain (Figure 5-3). The upper boundary condition were variable type boundary conditions. When there was no water addition either from rain or irrigation, upper boundary conditions were set at atmospheric pressure. Input data for precipitation, soil evaporation, and potential transpiration from the crop were specified in the input file ATMOSPH.IN. Since the crop canopy was completely closed after 23 June, long before the simulation period (July 12 to July 22), it was assumed that the soil evaporation was zero. The potential water flux across the soil surface was internally calculated by the program as the difference between precipitation and soil evaporation. Actual transpiration rate was also internally calculated in the program using the potential transpiration rate, surface width length and the root zone of an arbitrary shape. The details on these calculations are given in Simunek et al. (1994).

The potato root zone for both drip and sprinkler irrigation used in the simulations is shown in the Figure 5-2. The shape of this root zone is the best estimate based on the drying patterns presented in chapter 4. The lower boundary of flow domain is set as a Free Drainage condition with a unit hydraulic gradient. The lower boundary condition was implemented in the form of a variable flux boundary condition.

The left hand side boundary condition was set as an Impermeable Boundary for all nodes except nodes #13, 14, and 15 where the drip line was located (Figure 5-2). The boundary conditions at nodes #13, 14 and 15 were Dirichlet type boundary condition (head specified boundary condition). During the period when drip irrigation was applied, the hydraulic head at these nodes was set at zero. When no drip irrigation was applied, the boundary condition at the drip nodes was set to a no flow boundary condition (Impermeable Boundary).

The boundary conditions on the right hand side of the flow domain were set as an Impermeable Boundary. This boundary condition implies that there is no flow entering or leaving the flow domain from the right hand side during the entire simulation period. This is consistent with the assumption that the flow is symmetrical around the z-axis.

SOIL PHYSICAL PROPERTY CHARACTERIZATION

Simulations were run for the Verndale sandy loam (coarse loamy over sandy, mixed, frigid, Udic Argiboroll) at the Staples Irrigation Center, Staples, MN. The soil has three distinguished horizons: Ap horizon (0 - 26 cm), Bt horizon (26 - 40 cm), and C horizon (greater than 40 cm). Particle size distribution and hydraulic conductivity of all three horizons are given in Sexton (1993). Since water retention curves, (θ versus vs. h function) in Sexton's thesis were only for the Ap and Bt horizons, we also characterized the water retention characteristic curve for the C horizon using undisturbed soil cores. In addition to the water retention characteristics, we also measured the bulk density and saturated hydraulic conductivity of soil in these cores. The procedures for our physical and hydraulic characterization were similar to that of Sexton (1993).

Unsaturated hydraulic conductivity function

Unsaturated hydraulic conductivity function for various horizons were estimated from the water retention characteristic curves using the program RETC (RETention Curve, a computer program for quantifying the hydraulic functions of unsaturated soils by van Genuchten et al., 1991). The underlying assumptions in calculating unsaturated hydraulic conductivity from the water retention characteristics are given in van Genuchten et al. (1991). Briefly, the RETC program uses the parametric model of van Genuchten (1980) to represent the soil water retention curve and then uses a pore interaction model to calculate the unsaturated hydraulic conductivity function from the observed soil water retention data. The RETC program uses a nonlinear least-squares parameter optimization technique to estimate the model parameters from the observed water retention, and/or conductivity or diffusivity data. The method is based on partitioning the total sum of squares of the observed values into a part described by the fitted equation and a residual part of observed values around those predicted with the model (van Genuchten et al., 1991). The approach maximizes the sum of square associated with the model, while minimizing the residual sum of the squares. Figures 5-4 shows the comparison of the measured and the fitted water retention curves and Figure 5-5 shows the estimated hydraulic conductivity vs. water content curves for the Ap, Bt and C horizons using the RETC model. In Table 5-1 are listed the parameters of the water retention and relative hydraulic conductivity curves for the Ap, Bt, and C horizons.

INPUT WEATHER DATA

Water movement in a ridge furrow configuration under a growing potato plant was simulated using the hourly precipitation and potential evapotranspiration data from July 12 through July 22. Hourly precipitation data were taken from the Staples weather station and hourly evapotranspiration data was calculated from the TDR water content measurement as described in Chapter 4.

MODEL VALIDATION AND SENSITIVITY ANALYSIS

The simulated water content distribution from the SWMS_2D model were compared against the TDR measured values. The sensitivity analyses of the SWMS_2D model were run for the initial and upper boundary conditions, and the placement of drip line relative to the top of the ridge.

Table 5-1. Soil bulk density (ρ_b) and coefficients of van Genuchten's equations that describe water retention and hydraulic conductivity vs. water content relationships for the Verndale sandy loam. The values of the variables in van Genuchten's equations were estimated using the RETC program (van Genuchten et al., 1991).

		variables in van Genuchten's equations†				
Horizon (cm)	ρ_b	θ_s	θ_r	α	n	K_{sat}
	Mg m^{-3}	cm^3 cm^{-3}	cm^3 cm^{-3}	cm^{-1}		mm d^{-1}
Ap (0-26)	1.52	0.395	0.023	0.0431	1.280	1138
Bt (26-40)	1.73	0.333	0.000	0.0104	1.315	331
C (> 40)	1.56	0.412	0.000	0.0702	1.494	2880

† Soil water retention characteristics curve:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha h)^n]^m}$$

Hydraulic conductivity function:

$$K(h) = K_{sat} \frac{(1 - (\alpha h)^{n-1}[(1+(\alpha h)^n]^{-m})^2}{[1+(\alpha h)^n]^{m/2}} \quad ; \quad m = 1 - \frac{1}{n}$$

where θ_s and θ_r are the saturated and residual water contents, respectively; α, n and m are empirical constants; and K_{sat} is the saturated hydraulic conductivity.

RESULTS AND DISCUSSIONS

Since a symmetrical grid network greatly reduces the computer simulation time, we assumed that the drip line was exactly below the top of the ridge for our simulation. However, during excavation of the soil profile at the end of the field experiment, we noticed that the top of the ridge was not exactly above the drip line (chapter 4) but was 7 cm to left of the center of the ridge. Therefore, the comparisons between the simulated and measured wetting and drying patterns discussed in this chapter are qualitative. Except where noted, the drip line was assumed to be at 40 cm depth below the top of the ridge. All simulations were run starting at 0000 hour on July 12, 1994. Figure 5-3 shows the initial water content distribution corresponding to a matric potential of -33 kPa.

FIELD TEST OF THE MODEL

During field testing of the model, we observed that in simulation with sprinkler irrigation or rainfall, water remained in the top portion of the ridge for a long time (~2 hrs) after water application. Since we did not observe such phenomenon in the field, we knew our assignment of hydraulic properties for the top portion of the ridge must not be correct. As the top part of the ridge is generally loose compared to the lower part of the ridge, and since our measurements of hydraulic properties were done on a relatively undisturbed Ap horizon sample, we judged it to be necessary to add a new horizon (Ap0) to the original 3 horizons. Since no hydraulic measurements were made in the field for the Ap0 horizon, we used the sensitivity analysis and literature values to assign the hydraulic conductivity function for the Ap0 horizon.

In Figure 5-6 are shown the results of three simulations on soil wetting due to surface water addition by sprinkler irrigation. Each simulation represents a different hydraulic conductivity function for the Ap0 horizon. It was assumed that the shape of the hydraulic conductivity function was the same as that of the Ap horizon but all the values were 10 or 100 times greater than the values for the Ap horizon. A qualitative comparison with the measured wetting patterns (previous chapter's Figure 4-18) shows that the simulated patterns were close to the measured values when the hydraulic conductivity function of the Ap horizon was increased by 10 times (Figures 5-6b and 5-6e). The 10 time increase in the hydraulic conductivity function results in saturated hydraulic conductivity of 47.4 cm h^{-1} (11.4 m d^{-1}) for the Ap0 horizon. This value is close to the highest Ksat value reported in the literature for this soil type (Clapp and Hornberger, 1978). Therefore, for all our subsequent simulations we used a Ksat of 47.4 cm h^{-1} for the Ap0 horizon. In Figures 5-7 through 5-10, we present the comparison between the measured and simulated wetting and drying patterns for the drip and sprinkler irrigation treatments.

Drip Irrigation

A comparison between the measured and the simulated wetting patterns (water recharge) after an application of water through a drip line on July 12, 1994 is shown in Figure 5-7. Water was applied for 0.3 hours starting at 2000 hours. As expected, in both measured and the simulated conditions, water initially (2100 hrs) spread around the drip line in a circular pattern. With an increase in time (2300 hrs), water starting to move laterally as a results of the hydraulic impedance from the Bt horizon. However, there was slightly more movement of water to the left of the center of the ridge in the field than under the simulated conditions. This difference between the measured and simulated wetting pattern may be due to the differences in initial soil wetness between the field and the simulated experiment.

A comparison between the measured and the simulated drying patterns (water removal) under the drip irrigation is shown in Figure 5-8. As expected, in both measured and simulated conditions, more water was removed from the soil by transpiration during 1200 to 2000 hours than during 800 to 1200 hrs. However, the soil area affected by the root uptake was larger in the simulated pattern compared to the observed pattern. Conversely, the decrease in root zone water contents was the other way around. This suggests that the root zone area assigned in the simulations might be larger than the actual root zone area in the field experiment. Since no measurement of the root zone area or root density were made, it is difficult to test this discrepancy between the measured and the simulated values.

In general, the simulated soil wetting and drying patterns followed the trend in the measured values. However, there were some clear differences between the simulated and the measured wetting and drying patterns because of the uncertainties in the assignment of initial soil water content and the location of the root zone in our simulations.

Sprinkler Irrigation

A comparison of the measured and the simulated wetting patterns at 2200 hours on July 12 after an application of 1.8 cm water with a sprinkler irrigation is shown in Figure 5-9. For the simulation case, water uniformly infiltrated into the soil, however, the measured pattern showed a presence of some preferential transport in the shoulders of the ridge. This is expected because we had not made any provision of preferential pathways in our simulation. In other words, we assumed that the top of the ridge was spatially homogenous with respect to soil hydraulic properties as well as the water was applied uniformly over the whole ridge. Both these assumptions may not be the case in the field.

In Figure 5-10 is shown a comparison between the measured and the simulated drying patterns under sprinkler irrigation. As expected, more water was removed from the soil by transpiration from 1200 to 2000 hours than from 800 to 1200 hrs. However, the shape of the simulated drying patterns was different than the measured. Again, this difference may be due to our assignment of the shape of the root zone in these simulation.

In summary, there were some differences in the soil wetting and the drying patterns between the measured and the simulated cases under sprinkler irrigation. These differences may be because of the differences in the initial water content, root zone location and possibly due to the spatial variability of soil hydraulic properties in the ridge between the measure and the simulated cases.

SENSITIVITY ANALYSIS

In order to identify major factors that may affect percolation and thus nitrate leaching from a soil under a ridge-furrow configuration with a growing potato plant, we also conducted a sensitivity analysis of the SWMS_2D model. The sensitivity analysis characterized the differences in drainage as a function of 1) the amount of rain, 2) the initial water content, 3) the upper boundary conditions (stem flow and surface ponding), 4) the placement of the drip line, and 5) the irrigation application rate. All simulations discussed in this section were run for 240 hours (10 days). Consequently, the values reported in a series of Tables are the cumulative values at the end of the 240 hours of simulation.

Effect of Rainfall Amount on Percolation

Effect of rainfall amount on percolation/drainage was simulated by applying 1.5 cm h^{-1} rain for 2, 4, 6, 8 or 10 hours. The cumulative amount of water applied for these treatments was 3, 6, 9, 12 and 15 cm. In Figure 5-11 is shown an example of the wetting pattern for 15 cm rain. Rain started at 1000 hours and was over at 2000 hours on July 12. Starting at 2000 hours (when we stopped adding water) soil water content started to decrease as a result of drainage and root uptake. In Figure 5-12 is shown the variation in percolation as a function of time for different rainfall amounts. In general, the percolation increased with an increase in rainfall, however, noticeable drainage occurred when total rainfall was greater than 3.0 cm. This threshold drainage of 3.0 cm of water is equivalent to the unfilled porespace, a difference between the soil water holding capacity and amount of soil water at the initial soil water content. These trends are similar to the trends observed in the field measurements (Chapter 4).

Effect of Initial Soil Water Content on Percolation

The effect of initial soil water content on percolation was simulated at three initial soil wetness conditions corresponding to matric potentials of -3 kPa (wet condition), -33 kPa (field capacity), and -60 kPa (dry condition). Rain started at 1000 hours and ended at 1600 hours on July 12. Rainfall intensity was 1.5 cm h^{-1}. As expected, the wet soil had more percolation followed by soil at field capacity water content and then soil at the drier water content (Figure 5-13). This is because there was less room left in soil to hold additional rain water in wet soil conditions followed by soil at field capacity water content and then soil at the drier water content. The times when percolation appeared at the bottom of the profile were at 1000, 2200, and 4700 hours for wet, field capacity, and dry conditions, respectively. This means that the wetter soils, the earlier is the drainage. This is expected because the hydraulic conductivity of the wet soils is higher compared to that of the dry soils.

Effect of Stem Flow and Surface Ponding on Percolation

Based on dye movement experiments, Saffinga et al., (1976) implied that the potato leaf architecture was such that the rain water flowed towards the base of the potato stem, which in turn resulted in the preferential transport of water in the soil. In the following section, we discussed the simulation results where the effect of stem flow and variable flux condition at the upper boundary were incorporated. To demonstrate the effect of stem flow on soil wetting pattern (Figure 5-14) and percolation (Table 5-2), we set node #1 (the base of the potato plant) at saturation for a period of 0.3 hours and assume there was no surface water application on other parts of the ridge-furrow system. The simulation results are for the drip irrigation set-up but without water application by drip tube. As is apparent from Figure 5-14, initially water moved fast downward in the soil as a result of high Ksat and high matric potential gradient in the Ap0 horizon. However, when the wetting front reached the Ap horizon (conductivity was 10 time lower than that in the Ap0) water started to move laterally. At about 22 hours (2200 hour on July 13) after the start of water application at node #1, water was homogeneously distributed in both the Ap0 and the Ap horizons and there was no noticeable movement of water into the Bt horizon.

In Table 5-2 , we summarize the simulated amount of drip irrigation, ET, percolation, and change in soil water storage (ΔW) for various amounts of stem flow and surface ponding. Varying amounts of stem flow were simulated by varying the time for which the top of the ridge (node #1) was kept at saturation.

In general, there was an increase in percolation with an increase in stem flow. However, absolute quantities of drainage were smaller than the amount of water input from stem flow. This suggests that initial water condition and ET were such that most water entering the soil by stem flow was stored and subsequently taken up by plants.

Surface ponding effects were simulated by setting the node point #1 and all node points at the surface of the furrow (Figure 5-2) at saturation. We assumed that as a result of canopy, water was concentrated at the base of the stem and there was no water addition at nodes 43, 71, 97, and 123 at the top of the ridge. We further assumed that the water ran off the side of the ridge and accumulated in the furrow. For this sensitivity analysis, the listed nodes were set at saturation for 0.3 hours (similar to the stem flow simulation). As expected, water moved vertically in the center of the ridge similar to the simulations of stem flow (Figure 5-15). In the furrow, there was both vertical and horizontal (from the furrow towards the base of the ridge) flow. Eventually, both the water entering at the top of the ridge and furrow joined together leading to somewhat uniform water distribution in the Ap0 and Ap horizons (Figure 5-15). In general, water content of the soil profile was higher with stem flow and furrow ponding than the water content when there was only stem flow. This is expected because of higher water input from both stem flow and surface ponding in the furrows.

Effect of Drip Line Placement on Percolation

The effect of drip line placement on soil wetting and drying patterns is shown in Figures 5-16 through 5-18. Figure 5-17 is same as the simulation results in Figures 5-7 and 5-8. Three depths of drip line placement were 30 (Figure 5-16), 40 (Figure 5-17) and 50 cm (Figure 5-18) below the top of the ridge. In all these simulations, water was added through the drip tube for 0.3 hours. As discussed earlier, there was no noticeable drainage from the drip line placed at 40 cm depth (Figure 5-17). For this depth of placement, most of the water moved laterally because of the presence of the Bt horizon. There was also not much upward movement of water towards the top of the ridge. This lack of upward movement of water is important if fertigation is part of the management scheme in drip irrigation. Since the roots are relatively shallow in the early part of the season, fertilizer applied through the drip line will not be available to the plants. The above observation is consistent with the conclusions of Waddell (1994) who noted that reduced potato yield from subsurface drip with fertigation was because the starter fertilizer applied through drip irrigation was not available to the plants early in the season. Therefore, in drip irrigation systems where fertilizer is applied with water, it will be better if starter fertilizer is banded at the planting rather than applied through the subsurface drip. The exception will be the case where soil hydraulic properties are such that the water will rise to the top of the ridge or the drip is near the surface .

For the drip line located at 30 cm below the top of the ridge, there was some water movement towards the top of the ridge (Figure 5-16). This is because the 30 cm drip is located in a high conductivity Ap0 layer. Although there is some movement of water towards the top the ridge with 30 cm depth placement, this shallow placement of drip is disadvantageous because there is a risk that the drip line will be lifted out of the soil during potato digging thus causing problems with the harvesting operations as well as the expense of the drip line. Similar to the 40 cm depth drip placement, there was also no noticeable percolation from the drip placement at 30 cm depth for 0.3 hour of water application.

For the drip located at 50 cm depth (Figure 5-18), water mostly moved horizontally. This is because the drip was located in a low hydraulic conductivity (Bt) horizon. For this set-up, there was some movement of water to the C horizon, however, the magnitude of this downward movement was still small because the time for which the irrigation was applied was also small.

Since there were large differences in hydraulic conductivities among the horizons, the water application for the same time period resulted in larger differences in the amount of water infiltration from the drip. In order to quantify the effects of drip placement on the amount of drainage, we must have the same amount of water infiltration. To achieve the same level of water infiltration for all these levels of drip placement, we varied the time period over which the water was applied. In Figure 5-19 is shown the relationships between the amount of water infiltrated into the soil as a function of water application time for drip line placement at 30, 40, and 50 cm below the top of the ridge. These relationships were obtained by running simulations for different drip line placements and application times. Using these relationships, we estimated the water application time needed for any given amount of water infiltration into the soil profile for a given placement.

The simulation results on the interactions of the drip line placement and amount of irrigation on drainage are summarized in Table 5-3. Two levels of simulated drip irrigation applied were 0.54 and 1.08 cm (equivalent to 50 and 100 cm^3 of water, respectively). For a given level of drip irrigation, water application time varied according to Figure 5-19. The slight variation in the irrigation amount among the different drip placements for a given irrigation level is a result of error in reading the application time from the Figure 5-19.

For a given level of irrigation, the deeper the drip line placement, the greater was the percolation. However, these differences among various drip line placement and the water application levels were small. This is because the sum total of all the inputs (irrigation and rain) and outputs (ET and drainage) is less than the soil water holding capacity for any given irrigation level. The soil profile could hold 8.3 cm of water. Total water from irrigation and initial storage were less than 4.24 cm.

We also ran a sensitivity analysis on the impact of hydraulic conductivity of the Bt horizon on percolation losses for various combinations of drip line placement and amounts of water application (time for which the drip was run). In Table 5-4 is summarized the simulation results on the amount of drip irrigation, ET, DR, and ΔW for three depths of drip line placement and two amounts of water application when the hydraulic conductivity of the Bt horizon was increased by 3 fold. These results represent the simulation over a period of 10 days (July 12 through July 22). The procedure involved in these simulations were same as those described in the previous section except that the water application time was found from Figure 5-20. Comparison of the results between Tables 5-3 and 5-4 shows that with an increase in the hydraulic conductivity of the Bt horizon, there was an increase in amount of drainage for drip line installed at 40 and 50 cm depths below the top of the ridge. For the drip installed at 30 cm depth, the increase in the Ksat of Bt horizon did not cause any increase in the amount of drainage. However, since the net sum of water input and output was less than the water holding capacity, there was still not much drainage for all three levels of drip placement.

There were some differences in cumulative ET among various combinations of drip line placement and water application (Table 5-4). Averaged over three drip line placement depths, the average ET were 0.43 and 0.44 cm day^{-1}

for water application of 0.54 and 1.08 cm, respectively. These ET values are less than the potential ET of 0.51 cm day $^{-1}$ assigned for the 10 day simulation period. This indicates that water, to some degree, was limiting during the simulation for both levels (0.54 and 1.08 cm of water) of drip irrigation.

Simulated ET value is an important indicator as to whether or not the plant growth is under water stress. The best irrigation management should minimize drainage without reducing ET. Table 5-4 shows that water application of 1.08 cm resulted in a slightly higher ET without increasing in drainage, and thus this would be a better scenario among the two simulations tested here.

Effect of Initial Soil Wetness on Percolation

An additional sensitivity analysis was also run to evaluate the effects of initial soil wetness on the percolation. This simulation scenario, considered soil was at higher wetness (matric potential=-3 kPa) and the hydraulic conductivity of the Bt horizon was 1.38 cm h^{-1} (original value presented in Table 5-3). This simulation represent the condition where irrigation may occur right after a heavy rain. The procedure involved in these simulations were same as those described in the previous section. In Table 5-5 is summarized the simulation results of cumulative irrigation, ET, DR, and ΔW for a combination of two levels of water application and three levels of drip line placement. In general, percolation losses were higher for all combinations of drip line placement (drip line installed at 30, 40, and 50 cm depth below the top of the ridge) and the amounts of irrigation applied (0.54 and 1.08 cm). For a given depth of placement, the greater the amount of irrigation, the greater was percolation losses. ET from the crop was equal to 5.07 cm of the potential ET value, thus suggesting that water was not limiting in all cases.

Table 5-2. Effect of varying amount of stem flow on simulated ET, final change in soil water storage (ΔW), and drainage (DR) over a period of 10 days.

		0.3 hour†	1.0 hour	2.0 hour
Stem flow	cm	0.70	3.59	6.89
ET	cm	4.39	5.00	5.07
ΔW	cm	-3.71	-1.46	1.55
DR	cm	0.02	0.03	0.27

† Time over which stem flow occurred.

Table 5-3. Simulated amount of drip irrigation, cumulative ET, final change in soil water storage (ΔW), and cumulative drainage (DR) for a combination of various water application and drip line placement. Initial soil matric potential was uniformly distributed in the soil profile at -33 kPa.

	Irrigation Levels, cm					
	0.54			1.08		
	Drip Placement, cm					
	30	40	50	30	40	50
Applic. time, hour	0.39	0.50	0.68	1.0	1.41	1.81
Irrigation, cm	0.54	0.53	0.54	1.11	1.07	1.08
ET, cm	4.15	4.15	4.24	4.48	4.37	4.41
ΔW, cm	-3.62	-3.64	-3.72	-3.38	-3.32	-3.36
DR, cm	0.01	0.02	0.02	0.01	0.02	0.03

Table 5-4. Simulated amount of drip irrigation, cumulative ET, final change in soil water storage (ΔW), and cumulative drainage (DR) for a combination of various water application and drip line placement when Ksat of Bt was increased by 3 folds. Initial soil matric potential was uniformly distributed in the soil profile at -33 kPa.

	Irrigation Levels, cm					
	0.54			1.08		
	Drip Placement, cm					
	30	40	50	30	40	50
Applic. time, hour	0.40	0.33	0.23	1.00	0.91	0.67
Irrigation, cm	0.55	0.53	0.53	1.11	1.08	0.11
ET, cm	4.28	4.20	4.28	4.54	4.41	4.46
ΔW, cm	-3.75	-3.68	-3.77	3.46	-3.35	-3.37
DR, cm	0.01	0.01	0.01	0.01	0.02	0.02

Table 5-5. Simulated amount of drip irrigation, cumulative ET, final change in soil water storage (ΔW), and cumulative drainage (DR) for a combination of various water application and drip line placement. Initially soil was uniformly at a matric potential -3 kPa (wet condition).

	Irrigation Levels, cm					
	0.54			1.08		
	Drip Placement, cm					
	30	40	50	30	40	50
Applic. time, hour	0.60	1.05	1.50	1.30	2.50	3.50
Irrigation, cm	0.55	0.54	0.55	1.08	1.07	1.09
ET, cm	5.07	5.07	5.07	5.07	5.07	5.07
ΔW, cm	-8.43	-8.44	-8.44	-8.30	-8.35	-8.38
DR , cm	3.91	3.91	3.92	4.31	4.35	4.40

Effect of the Mode of Irrigation on Percolation Losses

We were also interested in evaluating the differences in percolation losses between the sprinkler and the drip irrigated plots if rain fell right after an irrigation. In Table 5-6 is summarized the results of the simulation on the amount of irrigation, ET, DR, and ΔW for the sprinkler and drip irrigated plots. These results represent a simulation for a period of 10 days (July 12 through July 22).

Simulations for both sprinkler and drip irrigated plots started at 0000 hour on July 12 with the initial condition shown in Figure 5-3. For the sprinkler irrigated plot, two irrigations of 1.6 and 1.7 cm (total of 3.3 cm of water) were applied at 2000 and 2100 hours, respectively, on July 12. For drip irrigated plot, irrigation was applied through drip placed at 40 cm below the top of the ridge starting at 2000 hours and ending at 2230 hours on July 12. This scheme resulted in the same depth of irrigation water as the sprinkler irrigation plot. This two and a half hour of drip irrigation time was found from Figure 5-19 at water application of 3.3 cm. Rain was simulated for 2 hours (starting at 2300 hours on July 12, one hour after the irrigation stopped, and ending at 0100 hours on July 13). A total of 3.0 cm rain was applied at a rate of 1.5 cm h^{-1}. The simulated results show that there was no difference in ET between the treatments and both treatments achieved the maximum ET of 5.07 cm and. However, there was a large difference in the amount of percolation. Percolation losses were 0.5 cm from the sprinkler irrigated plot compared to 0.1 cm from the drip irrigated plot. In this particular case, there was a reduction of 80% in percolation losses from the drip compared to the sprinkler irrigated plots. This supports our early hypotheses that irrigation with the buried drip could potentially reduce water percolation losses and thus nitrate leaching losses especially for events when rain occurs right after an irrigation.

Table 5-6. Comparison of simulated amount of drip irrigation, cumulative ET, final change in soil water storage (ΔW), and cumulative drainage (DR) between drip and sprinkler plots.

		Sprinkler Ir. Plot	Drip Ir. Plot
Rain.	cm	3.00	3.00
Irrigation	cm	3.30	3.30
ET	cm	5.07	5.07
ΔW	cm	0.73	1.13
DR	cm	0.50	0.10

SUMMARY AND CONCLUSIONS

It is somewhat difficult to match the simulated wetting and drying patterns against the measured values using a detailed mechanistic model such as SWMS_2D
because of the difficulty of obtaining detailed soil hydraulic characterization as well as initial and boundary conditions. Nevertheless, the SWMS_2D model is useful in predicting trends and also in outlining factors that may be important in minimizing percolation and nutrient leaching losses through soils.

The simulation results of wetting pattern with the drip line at 40 cm depth in the Verndale sandy loam showed that there was not much water movement towards the upper part of the ridge. This was consistent with our field observations. This finding implies that a starter fertilizer applied through the subsurface drip will not be available to plants because of insufficient root development and lack of water movement toward the surface. Although, the shallow drip line placement showed greater movement of water towards the top of the ridge this scenario has a disadvantage. During potatoes harvest, the drip lines will be ripped thus adding to the expense of laying the new drip line every year. Therefore, a better strategy for starter fertilizer application may be to keep the drip line at around 40 cm depth but band apply the starter fertilizer.

Sensitivity analysis results showed that the wet soil profile had more percolation followed by the profile at field capacity water content and then soil at the drier water content. This is expected as there is less room to hold additional rain water in wet soils. The simulation results also showed that the effect of stem flow on percolation losses was minimal. This may be because the SWMS_2D model does not account for cracks that occur in the field as a result of potato tuber expansion (Chapter 4).

The sensitivity analysis of the various factors showed that irrigation water applied through the buried drip could reduce water percolation losses compared to sprinkler irrigation method especially if a rain occurs right after irrigation.

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The authors wish to thank Dr. van Genuchten for providing us with the RETC and the SWMS_2D models. We also thank Dr. J. Simunek for his constructive advice on determining the grid net work and handling drip irrigation application during the simulations by the SWMS_2D model.

REFERENCES

Annandale, J. G. 1991. Two dimensional simulation of nitrate leaching in potatoes. Ph. D. dissertation. Washington State University, Pullman, WA.

Bresler, E. 1975. Two dimensional transport of solute during nonsteady infiltration from a trickle source. Soil Sci. Soc. Am. J. 39:604-613.

Clapp, R. B., and G. M. Hornberger. 1978. Empirical equation for some soil hydraulic properties. Water Resou. Res. 14:601-064.

van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892-898.

van Genuchten, M. Th., F. J. Leij and S. R. Yates. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils. Technical report #: EPA / 600/ 2-91/ 065. US-EPA.

Gregory, P. J. and L. P. Simmonds. 1992. Water relations and growth of potatoes. In (Ed. Paul Harris). The Potato Crop, Chapman and Hall, London, 215-246.

Healy, R. W. and Warrick, A. W. 1988. Generalized solution to infiltration from a surface point source. Soil Sci. Soc. Am. J. 52: 1245-1251.

Klaseus, T. G., G. C. Buzicky, and E. C. Schneider. 1988. Pesticides and groundwater: Survey of selected Minnesota wells. Report for the Legislative Commission on Minnesota Resources, Minnesota Dept. of Health and Minnesota Dept. of Agriculture.

Mallawatantri, A. P. 1994. Processes and factors influencing fate and movement if agrochemocals in rainfed and irrigated management. Ph. D. dissertation. Washington State University, Pullman, WA.

Myette, C. F. 1984. Groundwater quality appraisal of sand plain aquifers in Hubbard, Morrison, Otter tail, and Wadena counties, Minnesota. U.S. Geological survey. Water-Resources Investigations Report 84-4080. St. Paul, MN.

Saffigna, P. G., C. B. Tanner, and D. R. Keeney. 1976. Non-uniform infiltration under potato canopies caused by interception, stemflow, and hilling. Agron. J. 68:337-342.

Sexton, B. T. 1983. Influence of nitrogen and irrigation management on corn and potato response and nitrogen leaching. M.S. thesis, Univ. of Minn., St. Paul, MN.

Simunek, J., M. Th. van Genuchten, R. Zhang and T. Vogel. 1993. The CHAIN_2D code for simulating two-dimensional variably saturated water flow, heat transport, and transport of solute involved in sequential first-order decay reactions. Research report. U.S. Salinity laboratory, ARS. U.S.D.A. Riverside, CA.

Simunek, J., T. Vogel and M. Th. van Genuchten. 1994. The SWMW_2D code for simulating water flow and solute transport in two-dimensional variably saturated media (Version 1.2). Research report No. 132. U.S. Salinity laboratory, ARS. U.S.D.A. Riverside, CA.

Timlin, D. J., G. C. Heathman, and L.R. Ahuja. 1992. Solute leaching in crop rows vs. interrow zones. Soil Sci. Soc. Am. J. 56:384-392.

Waddell, J. 1994. Evaluation of drip and sprinkler irrigation and N management schemes on potato production and N leaching losses. PhD thesis research in progress.

Warrick, A. W. 1985. Point and line infiltration: calculation of the wetted soil surface. Soil Sci. Soc. Am. J. 49: 1581-1583.

Wu, L., J. M. Baker and R.R. Allmaras. 1995. Numerical and field evaluation of soil water sampled by suction lysimeters. J. Environ. Qual. 24:147-152.

Zhang, R. 1994. Micro-irrigaiton for optimaum crop productivity and minimum groudwater contamination. Presentation made at the W-128 meeting in Hawaii, October, 1994.

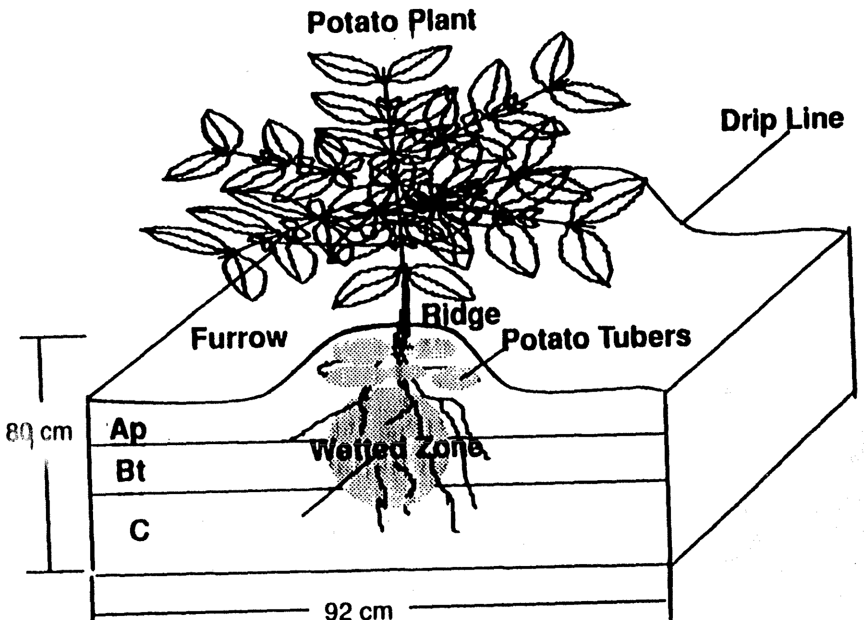


Figure 5-1. Physical model of soil wetting with a drip in a ridge-furrow system with a growing potato plant.

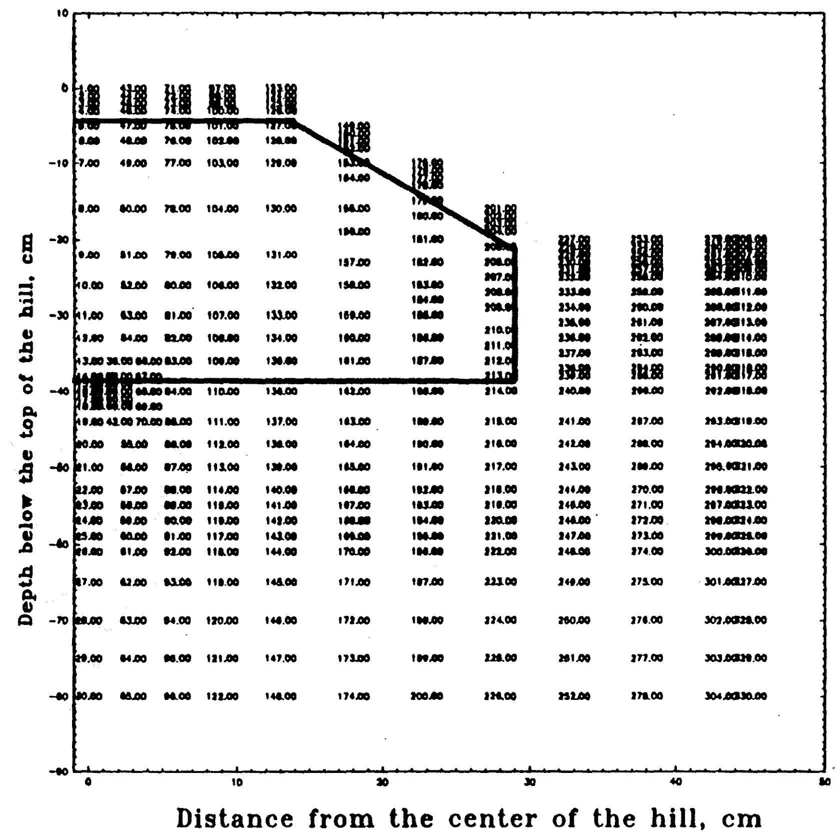


Figure 5-2. Grid net work used in the simulation of water movement with the SWMS_2D model. The area inside the solid line represent the potato root zone for both the drip and the sprinkler irrigation system.

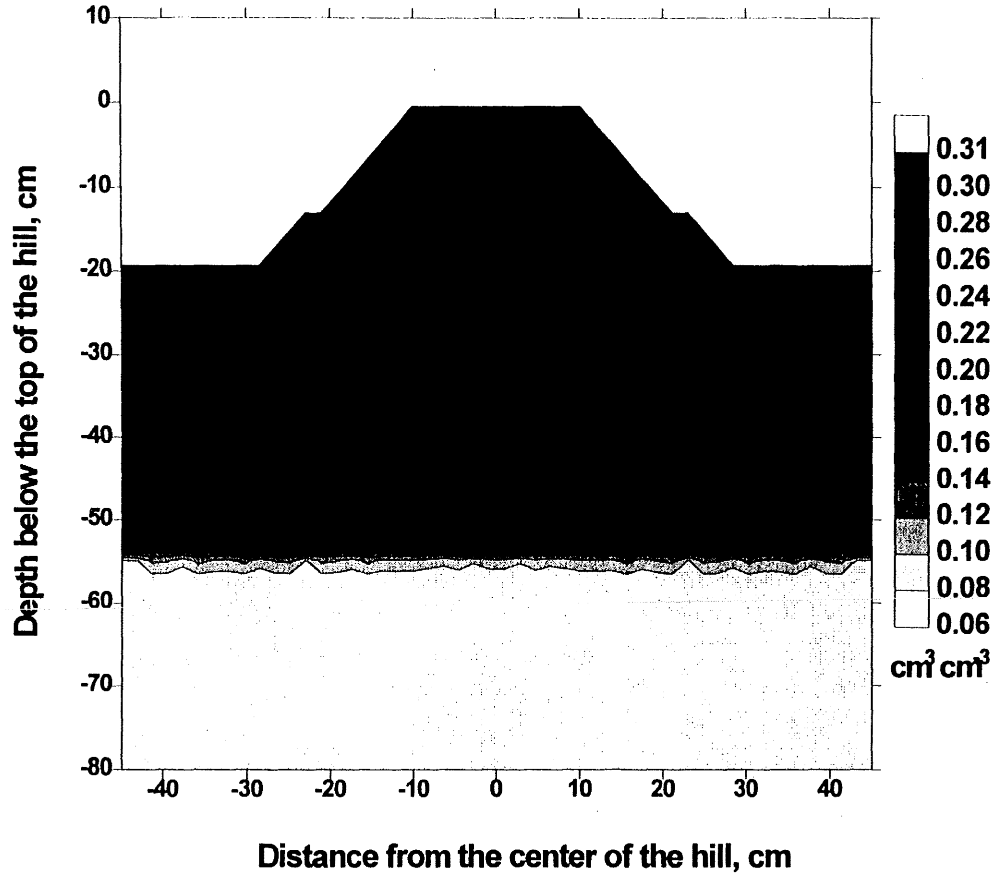


Figure 5-3. Initial (0:00 hour on July 12) soil water content profile used in the simulations with the SWMS_2D model.

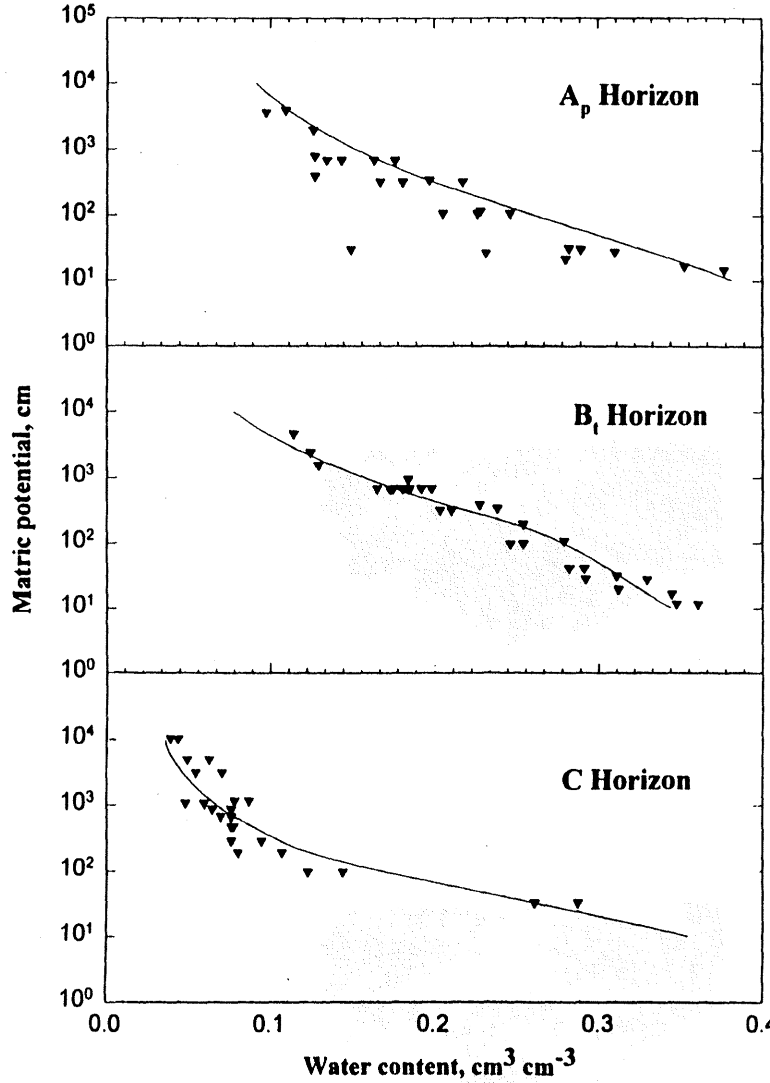


Figure 5-4. Water retention curves for the A_p, B_t and C horizons of Verndale sandy loam at Staples, MN. Retention curves were fitted with the RETention Curve (RETC) program (van Genuchten et al., 1991).

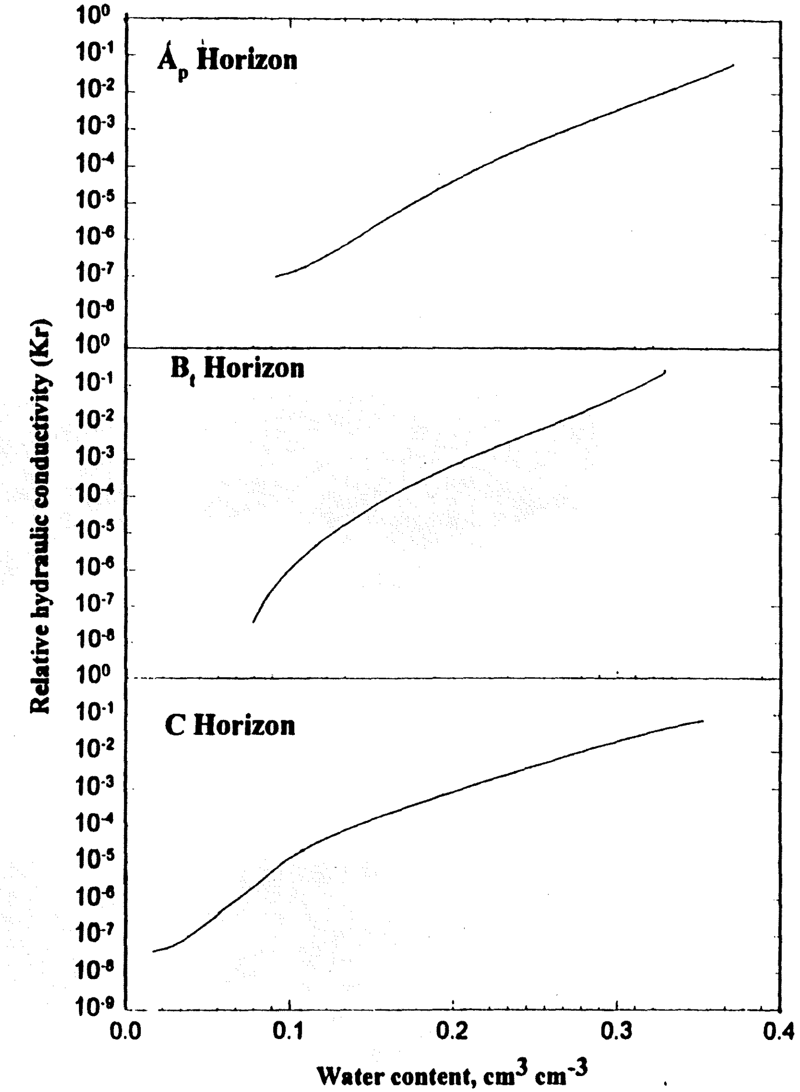


Figure 5-5. Relative hydaulic condutivities for the A_p, B_t and C horizons of Verndale sandy loam at Staples, MN. Kr curves were fitted with the RETC program (van Genuchten et al., 1991).

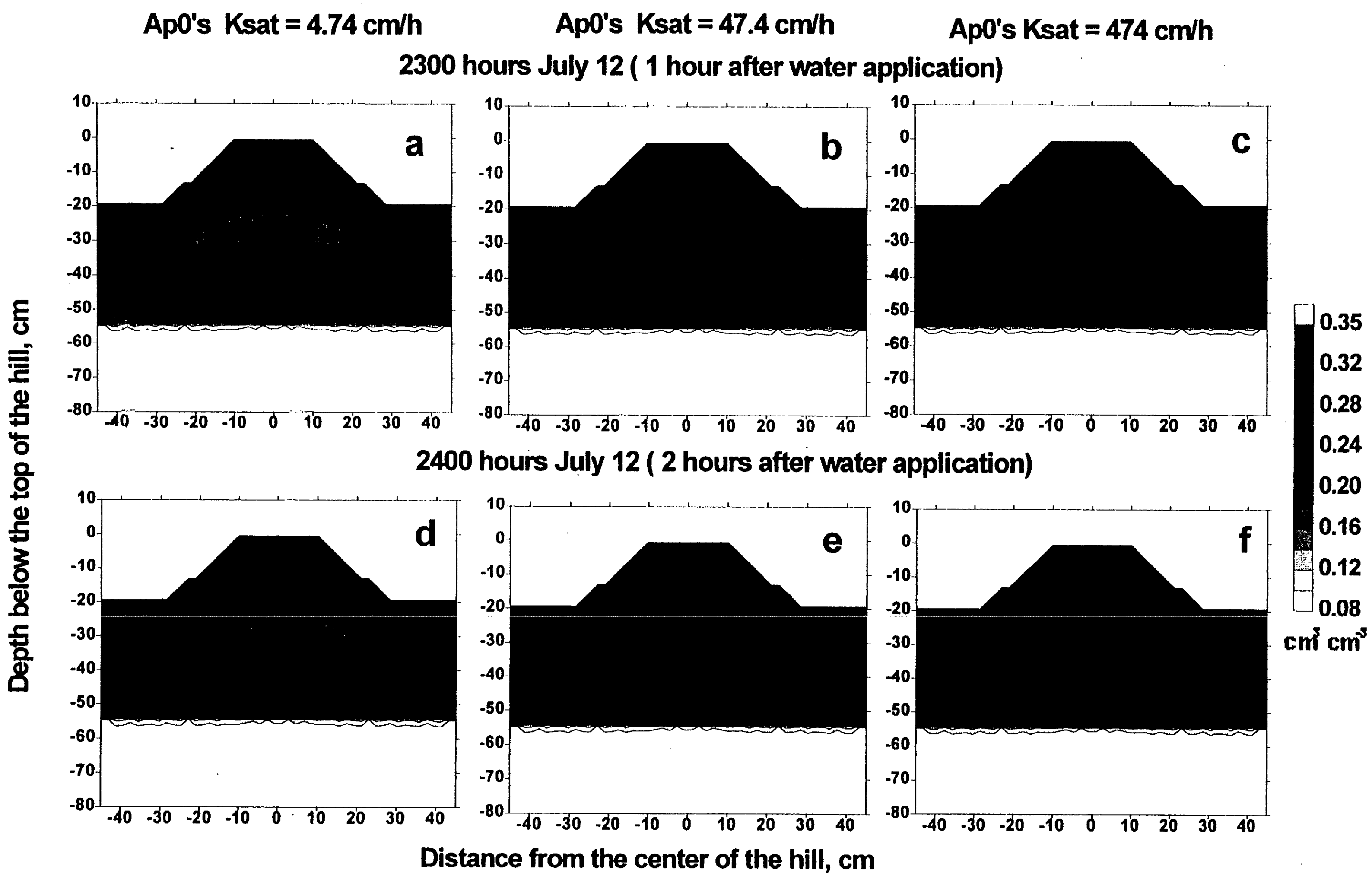


Figure 5-6 Effect of Ksat of the top layer (Ap0) on the simulated wetting patterns with 1.8 cm of rainfall starting at 2200 hours on July 12.

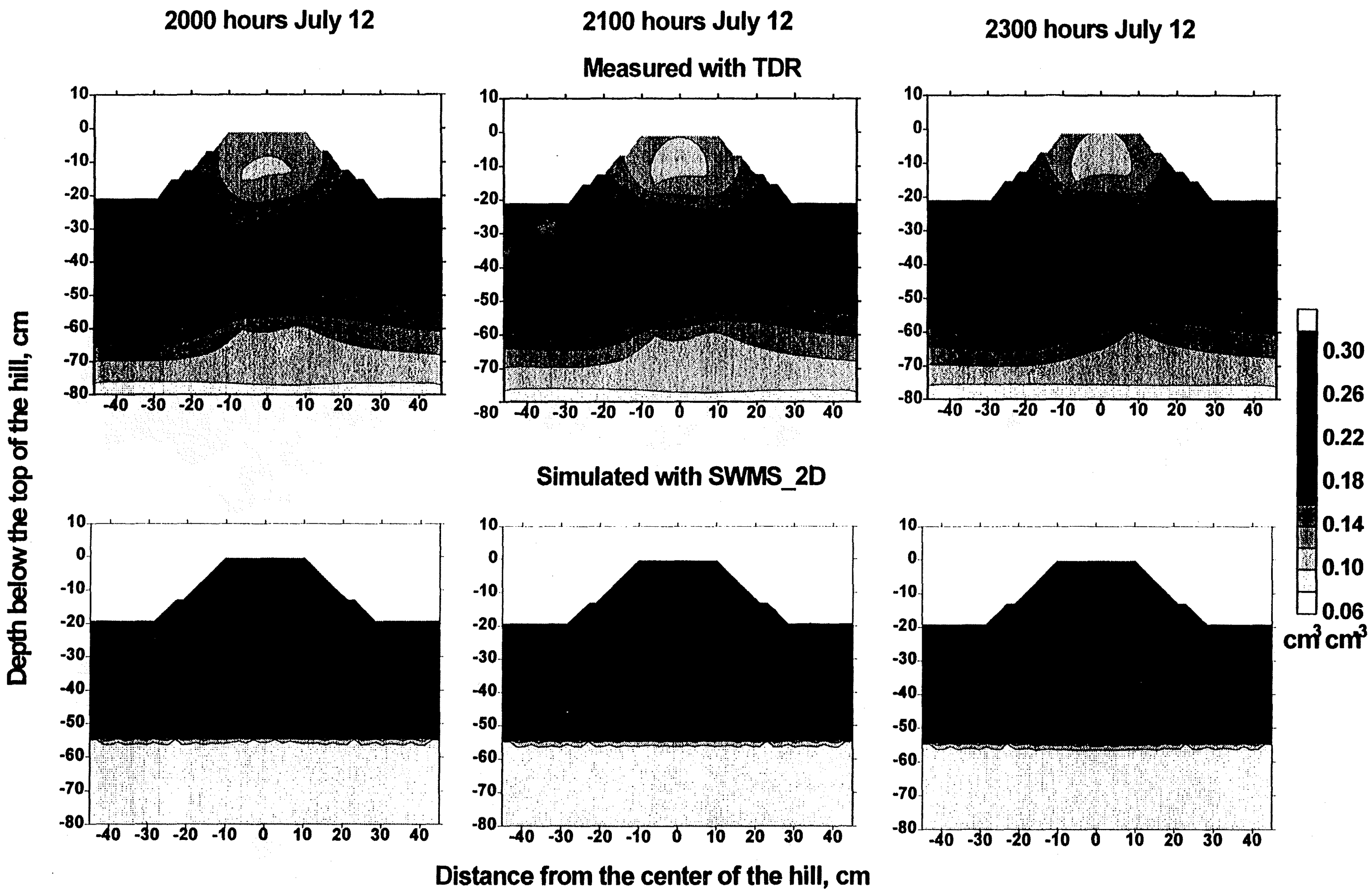


Figure 5-7. Comparisons between the measured and the simulated wetting patterns after a drip irrigation for 0.3 hours.

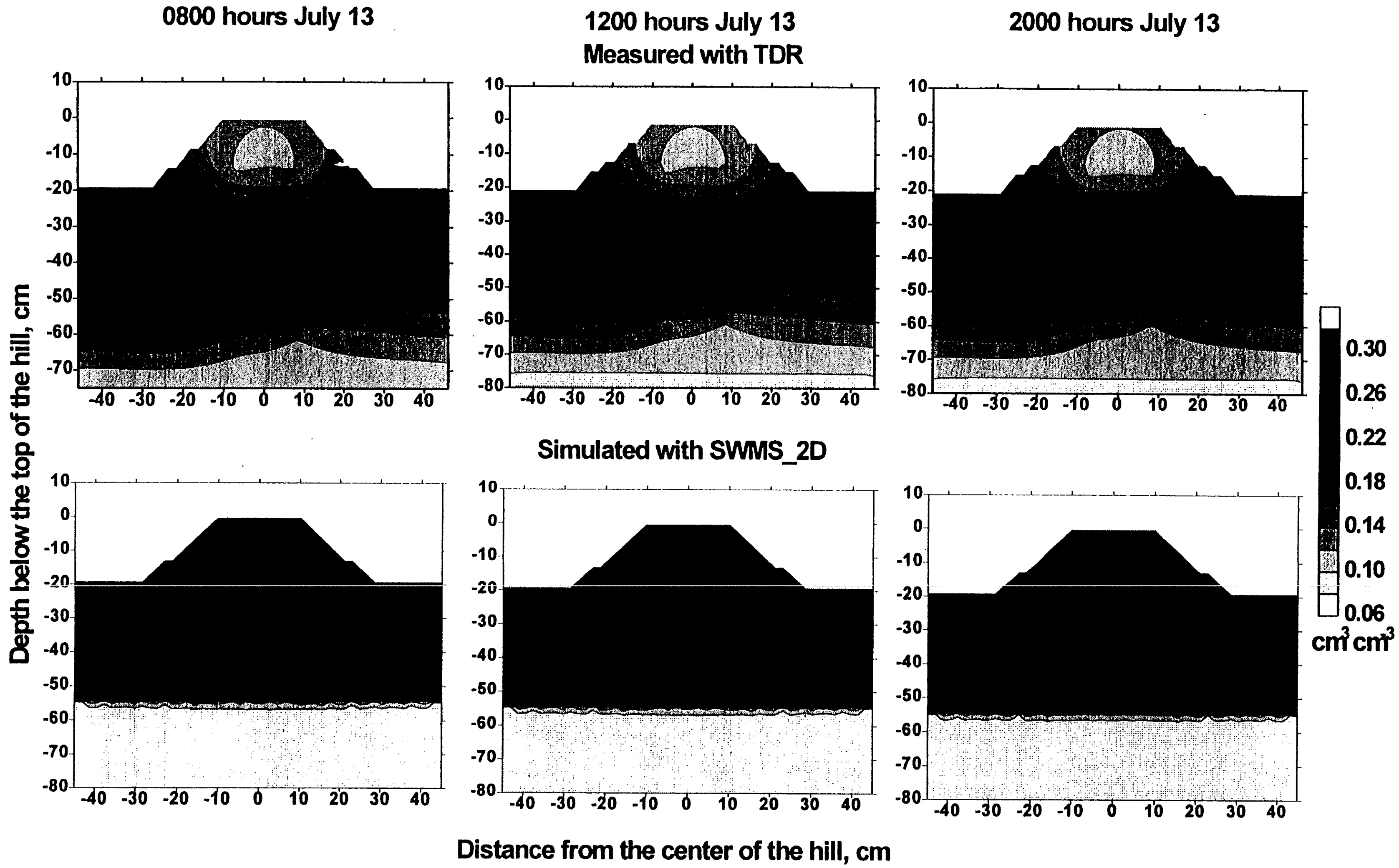


Figure 5-8. Comparisons between the measured and the simulated drying patterns under a drip irrigation.

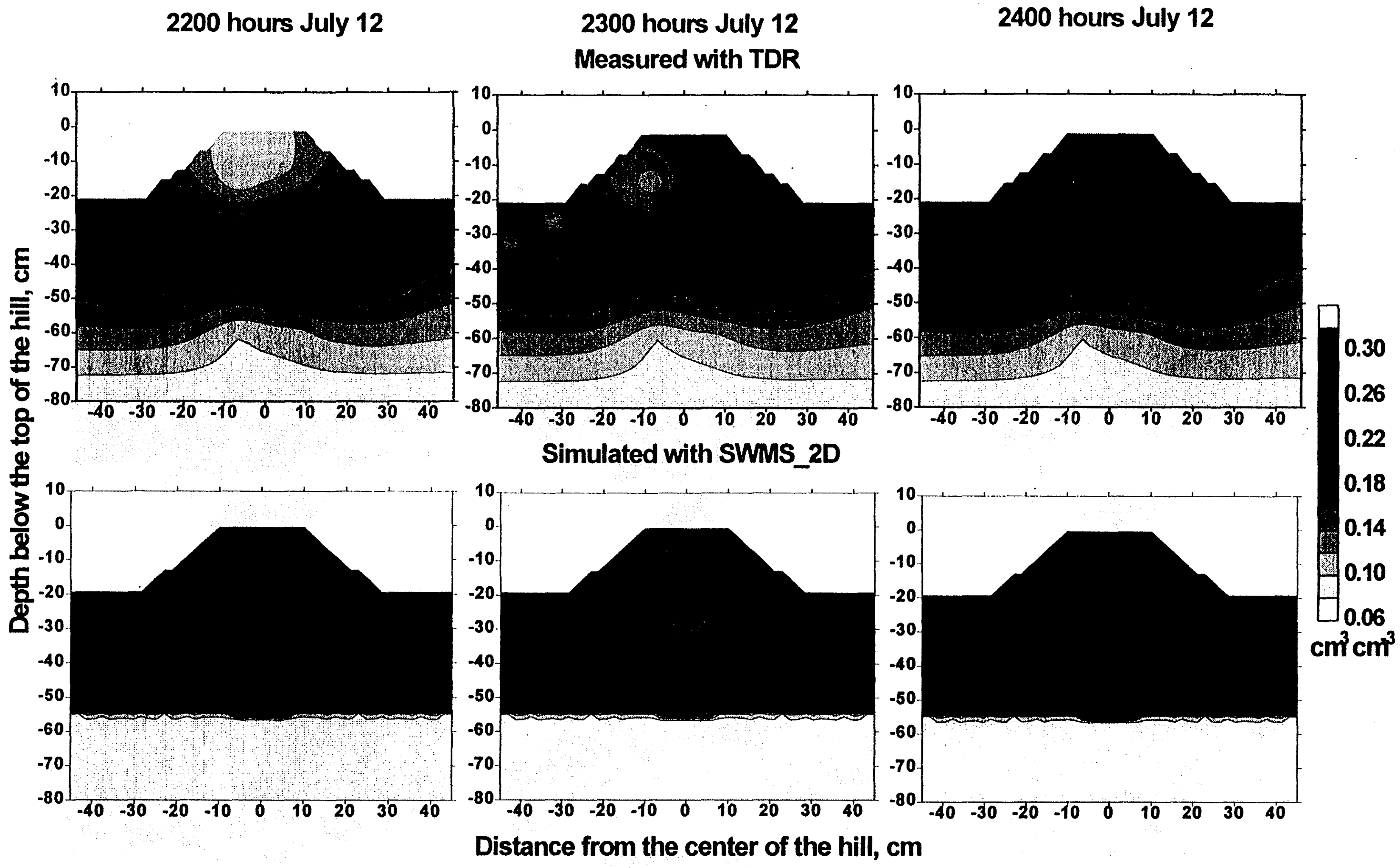


Figure 5-9. Comparison between the measured and the simulated wetting patterns after water application of 1.8 cm with a sprinkler irrigation starting at 2200 hours on July 12.

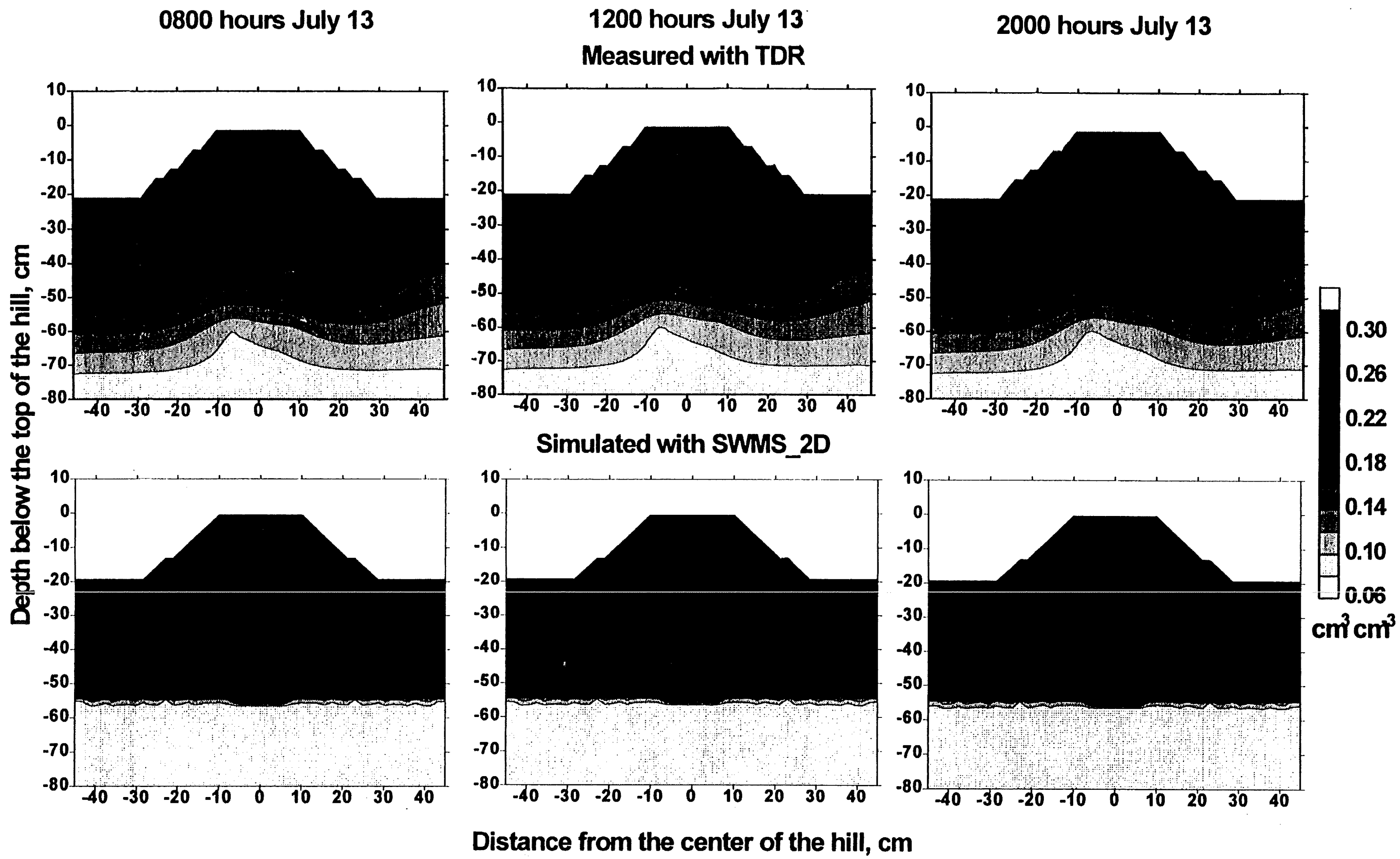


Figure 5-10. Comparison between the measured and the simulated drying patterns under a sprinkler irrigation.

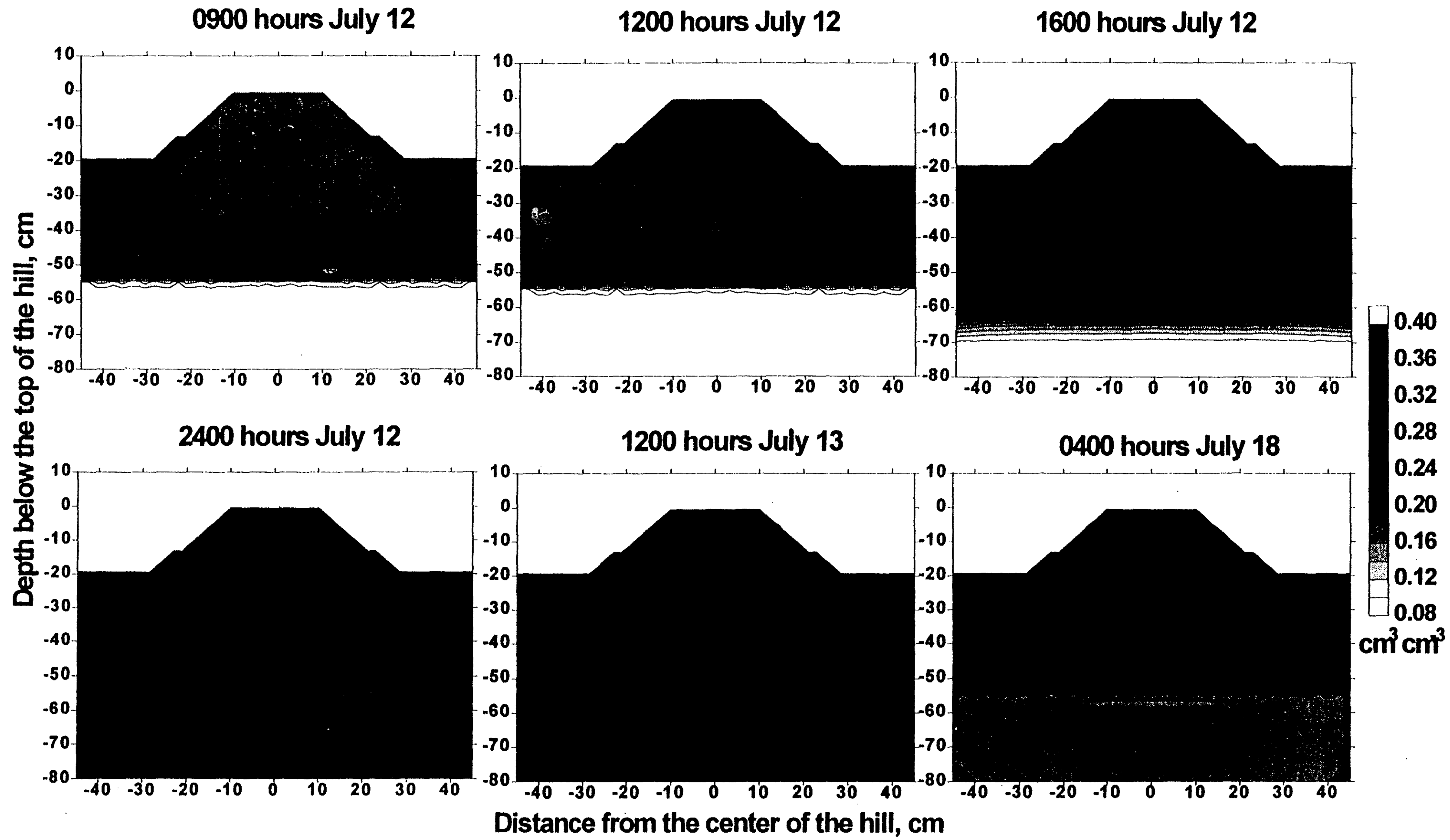


Figure 5-11. Simulated soil water content distribution as a function of time after an application of 15 cm of continous rain (1.5 cm /h for 10 hours). Rain started at 1000 hours and ended at 1900 hours on July 12, 1994. Ksat of Ap0 is 10 times higher than Ksat of Ap.

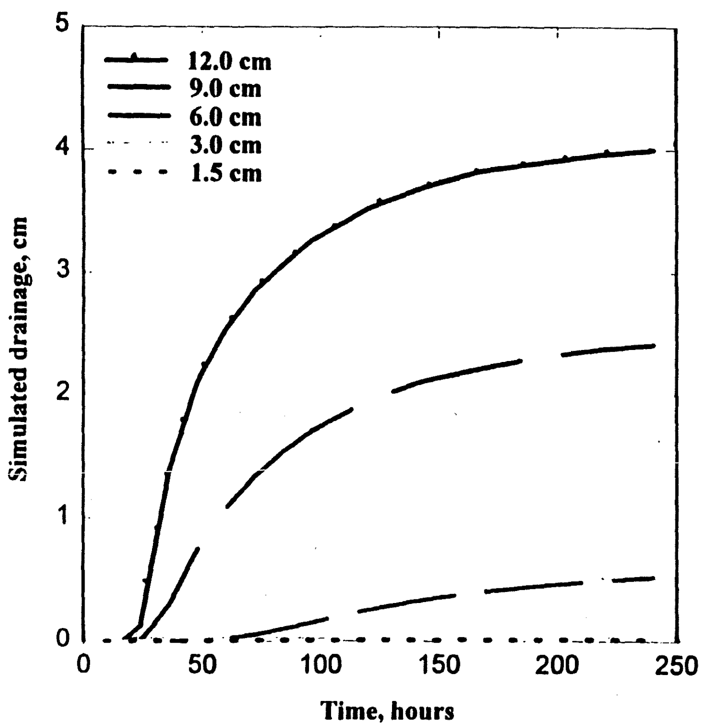


Figure 5-12. Simulated drainage as a function of time for different rainfall amounts. Initially (0000 hour on July 12), soil was uniformly at a matric potential of -33 kPa.

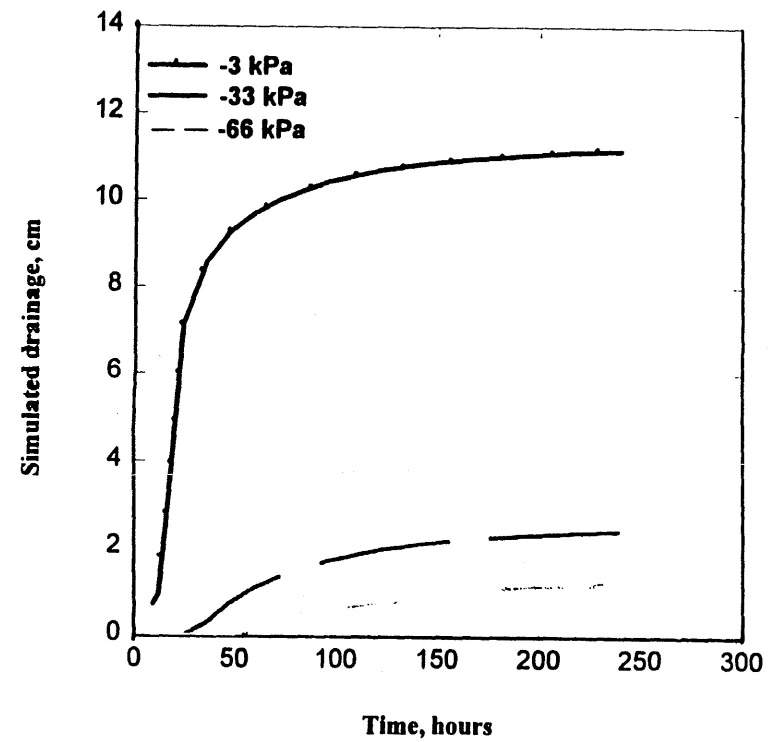


Figure 5-13. Simulated drainage as a function of time for three wetness conditions. Matric potential of -3, -33, and -66 kPa represent the wet, normal (field capacity), and dry soil conditions. Simulated drainage is after a rainfall of 1.8 cm.

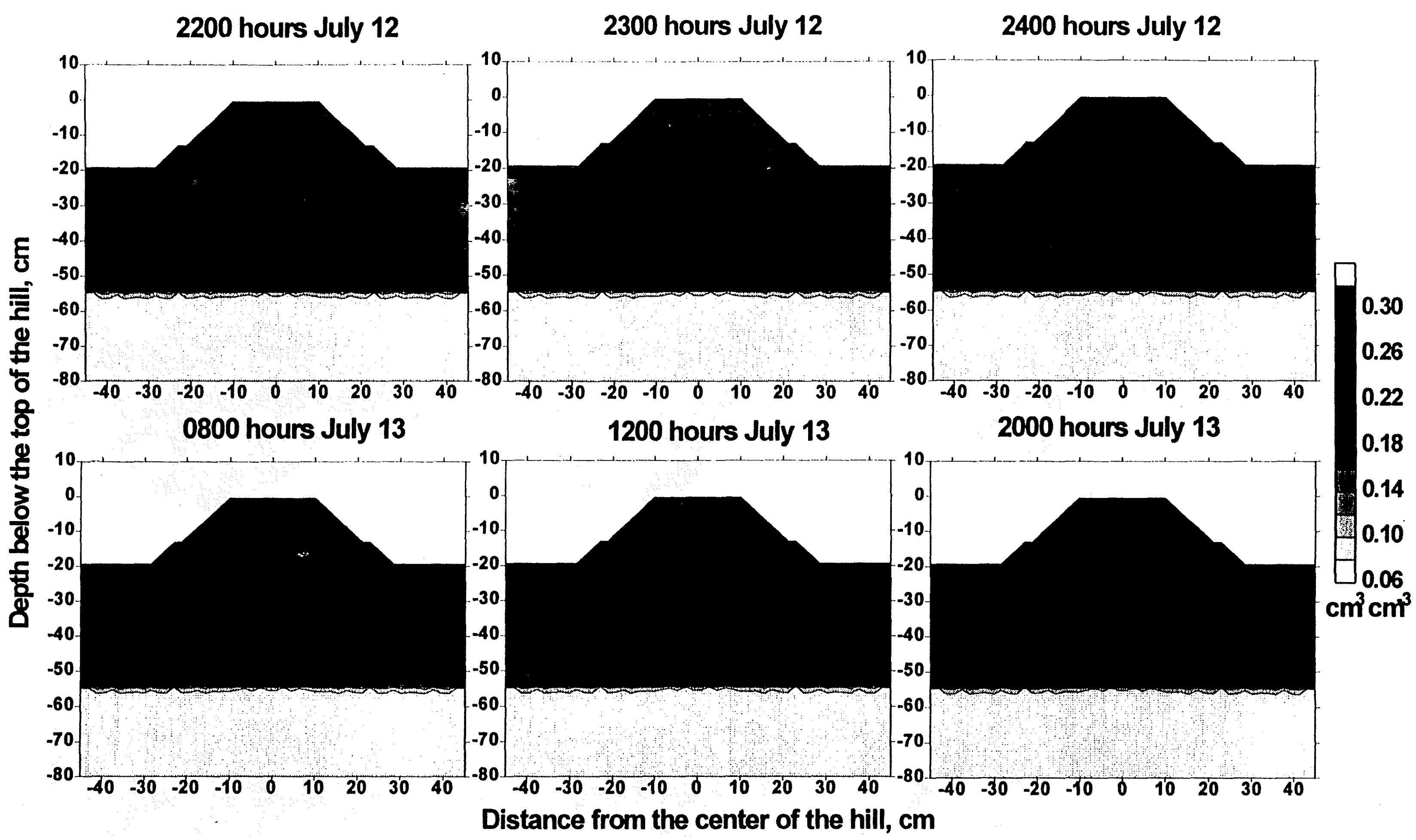


Figure 5-14. Simulated wetting patterns with stem flow in the sprinkler irrigated plot. Ksat of Ap0 was 10 times greater than the Ksat of Ap. Stem flow was simulated for 0.3 hours.

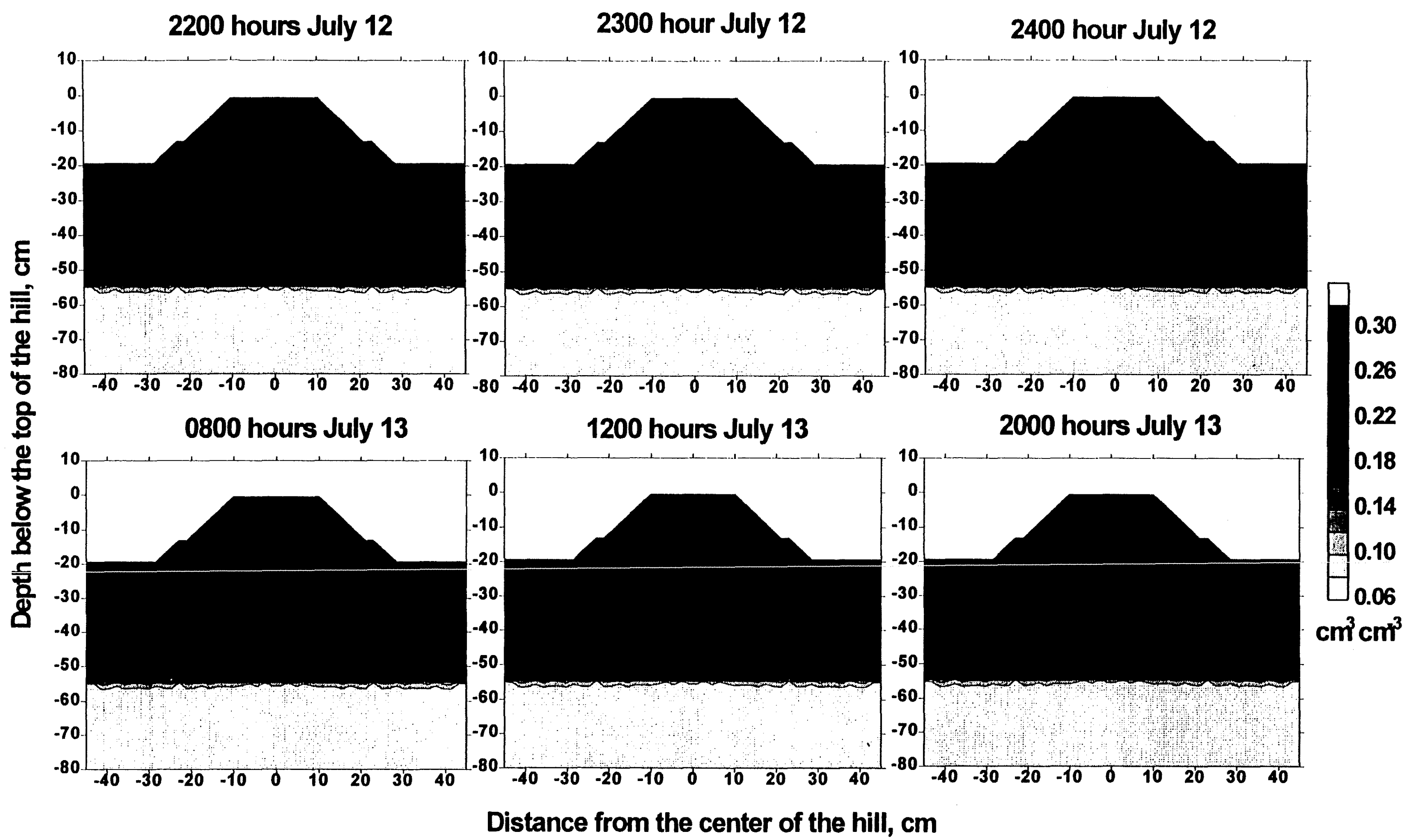


Figure 5-15. Simulated wetting patterns with stem flow and surface ponding in furrows. Ks of Ap0 was 10 times greater than Ksat of Ap. Stem flow was simulated for 0.3 hrs.

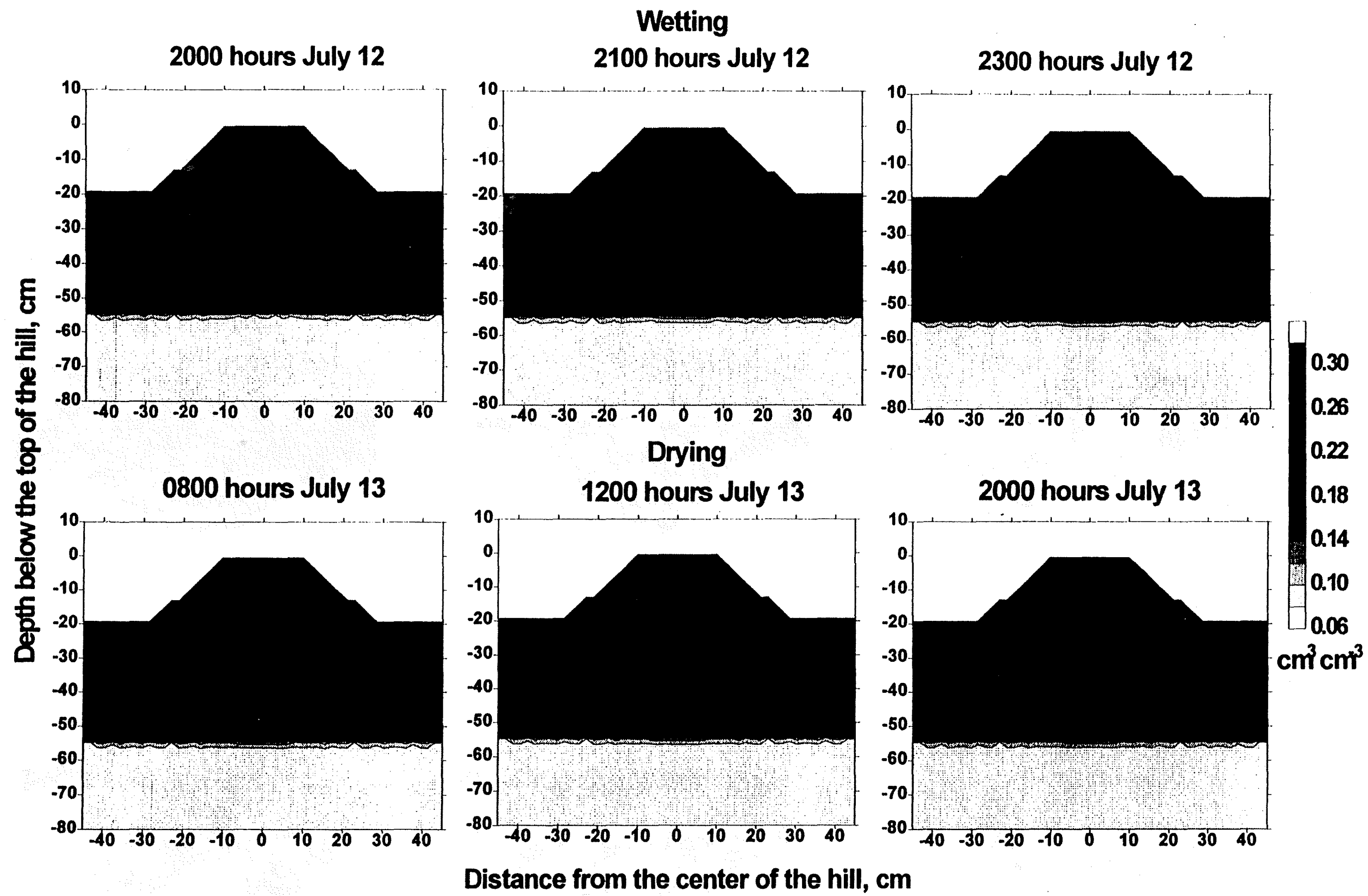


Figure 5-16. Simulated wetting and drying patterns for the drip irrigation treatment when drip was installed at 30 cm below the top of the hill.

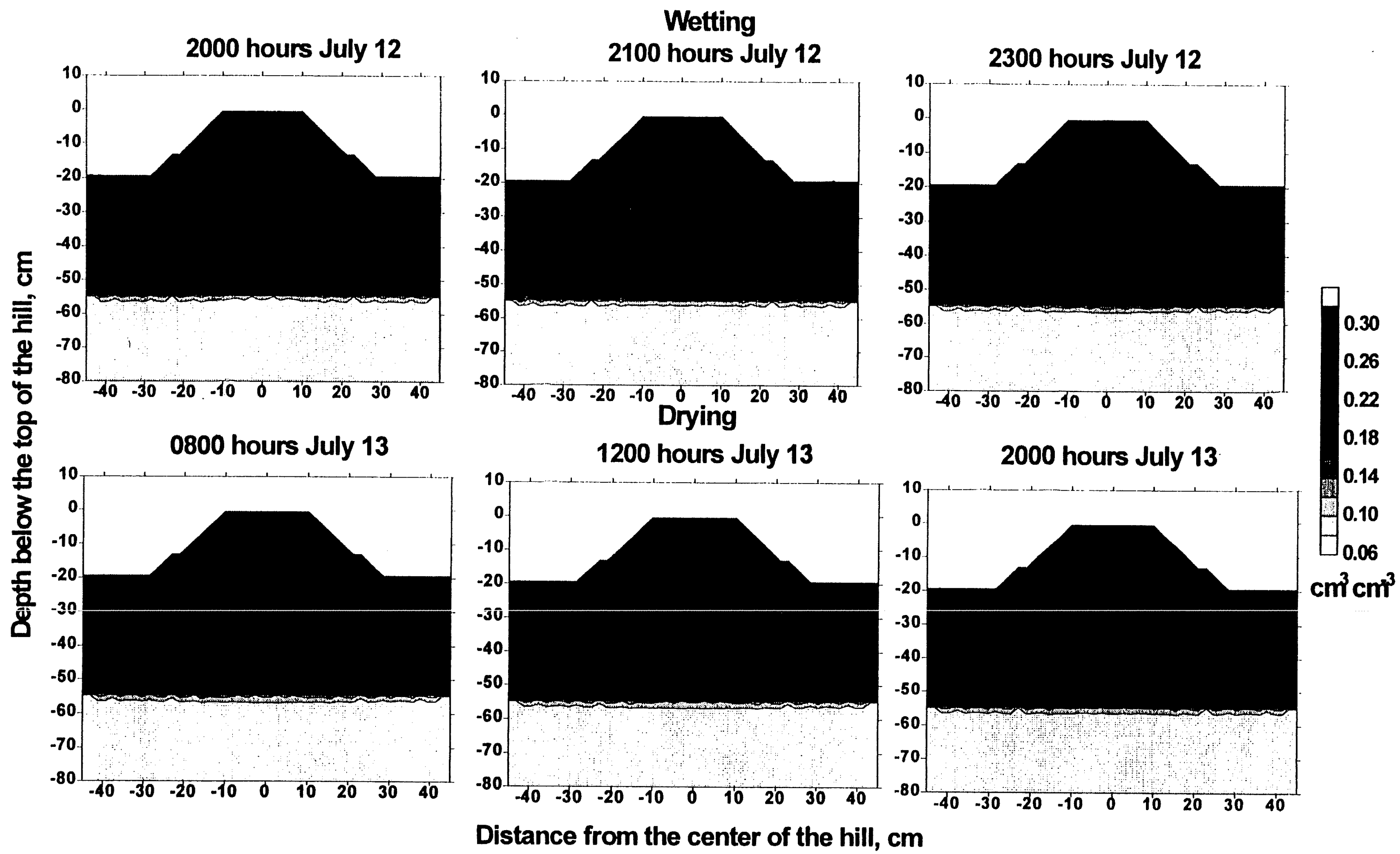


Figure 5-17. Simulated wetting and drying patterns for the drip irrigation treatment when drip was installed at 40 cm below the top of the hill.

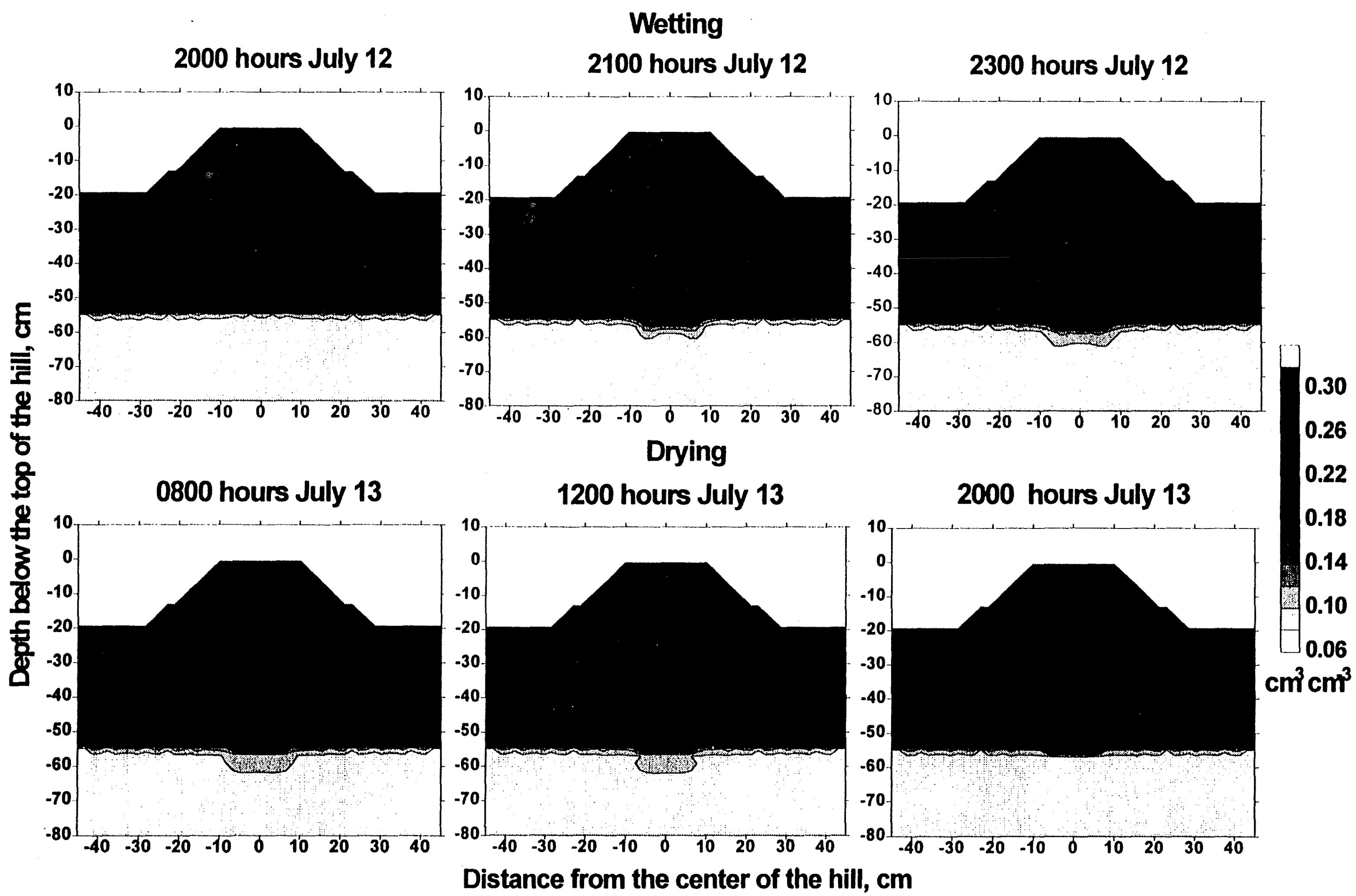


Figure 5-18. Simulated wetting and drying patterns for the drip irrigation treatment when drip was installed at 50 cm below the top of the hill.

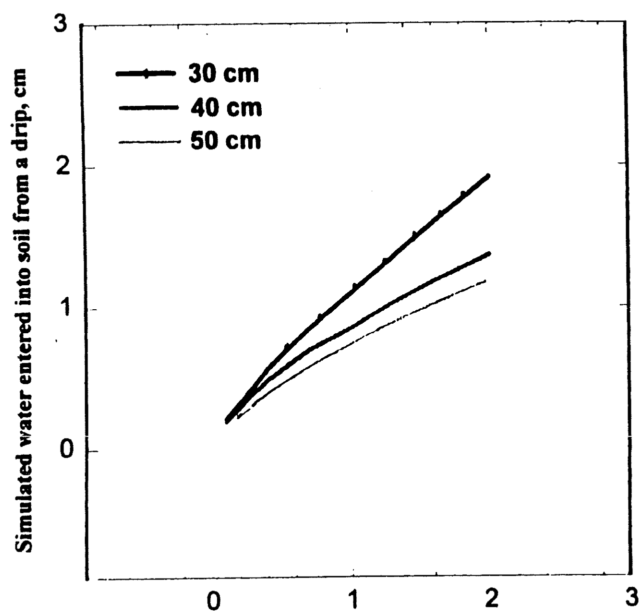


Figure 5-19. Simulated volume of water entering the soil from a drip line as a function of water application time for three (30, 40, and 50 cm below the top of the ridge) drip line placement. Initially, soil was at a matric potential of -33 kPa.

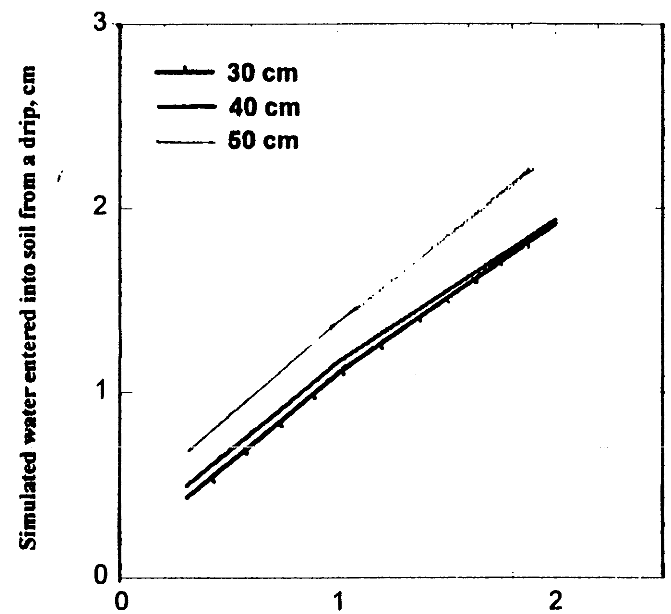


Figure 5-20. Simulated volume of water entering the soil from a drip line as a function of water application time for three (30, 40, and 50 cm below the top of the ridge) drip line placement. Initially, soil was at a matric potential of -33 kPa.
The Ksat of Bt was increased by three folds.

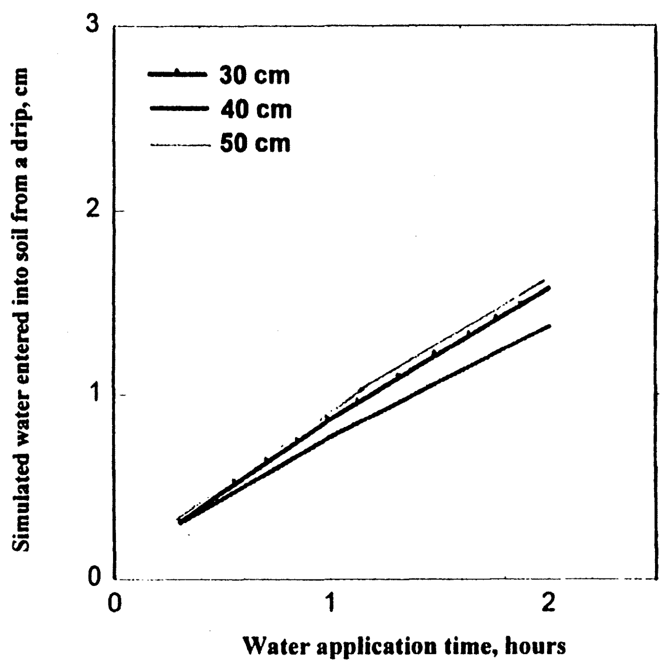


Figure 5-21. Simulated volume of water entering the soil from a drip line as a function of water application time for three (30, 40, and 50 cm below the top of the ridge) drip line placement. Initially, soil was at a matric potential of -3 kPa (wet).

Final Report for LCMR Project: Managing Agricultural Environments of North-Central Minnesota Sandy Soils

Activity E.3. Status. Determine soil conditional probabilities for percolation on north-central Minnesota sandy soils. Measurements and modeling to determine soil temperature and moisture characertistics.

E. Objective: Develop models for BMPs that consider movement of water, nitrogen and herbicides..

E.3. Activity. Determine soil conditional probabilities for percolation on north-central Minnesota sandy soils. Measurements and modeling to determine soil temperature and moisture characteristics. Subdivisions for project reporting include:

E.3.1 Historical climatological distributions
E.3.2 Field measurements and models for soil temperature and moisture
E.3.3 Probability distributions of climatic variables
E.3.4 Applications of climatic data to spray occasions

E.3.a. Context within project.

E.3.b. Methods

E.3.c. Materials

E.3.d. Budget

E.3.e. Timeline

E.3 Status: Historical climatic distributions for six locations in the north-central region of Minnesota show some degree of spatial variability, primarily due to latitudinal position since the region stretches approximately 150 miles from south to north. The temporal, or year to year variability is much greater than the spatial variability. Extreme events such as very short growing seasons, 100 degree temperatures and 4 inch rainfalls generally occur less than five percent of the time and cannot be mediated by existing management practices anyway.

The only location with a soil temperature record of any length was Staples Irrigation Center (1983-1993). The temporal pattern in both the four inch and eight inch depth shows considerable variability in the early spring and fall periods, with lesser variability during the summer months. Average temperatures at a depth of four inches reach 50 degrees F or greater during the last week of April. This is sufficient to trigger more active mineralization rates from nitrogen sources in the soil and also indicates that crops sown in mid to late April should adequately germinate. The degree to which soil temperatures are moderated by irrigation is unknown on these soils, but may be useful to investigate in order to fine-tune site specific management of fertilizer and manure applications which supply nitrogen sources subject to mineralization rates highly regulated by a variable soil environment.

Soil moisture retention in the north-central sands is generally poor, especially in the near surface layers. Volumetric field capacity for soil moisture in many of these sands ranges from 15 to 18 percent, while volumetric wilting point moisture content ranges from 6 to 8 percent. This equates to an available water holding capacity ranging from 1.0 to 1.3 inches per foot of soil. A soil moisture submodel from CERES-Maize (1986), available through the Midwest Climate Center, was run on a composite climatic data set (using multiple stations) for north-central Minnesota covering the period from 1951-1993. The resulting temporal distribution of soil moisture in the region showed that beginning in mid July and lasting well into September, soil moisture levels in the top 60 inches are at their lowest levels, commonly about half of available water holding capacity. In fact over a quarter of the time during late July and early August, available soil moisture values are less than 20 percent. This corresponds to the peak irrigation season for most crops in the region when rainfed soil moisture is supplemented heavily by overhead sprinkler applications.

Many irrigators in the north central sands use estimates of potential evapotranspiration on a daily basis coupled with monitoring soil moisture levels to help schedule irrigations during the crop season. However, little use is made of historical patterns of potential evapotranspiration and temporal soil moisture probabilities to critically look at irrigation design capacities. In addition, weather forecast probabilities are under-utilized in making decisions about when to apply irrigation as well as how much to apply. Probability of precipitation forecasts (POPs) and quantified precipitation forecasts (QPF) are available daily from the National Weather Service Forecast Offices in Minnesota, but are rarely used in irrigation decisions. Utilizing these information resources more fully should improve site-specific management of irrigation systems on the soils of north-central Minnesota. A pilot effort with some members of the North-Central Irrigators Association has been initiated to test this hypothesis.

Probability distributions for precipitation at the six climatic locations in the region, show that there is a twenty five percent chance of receiving 1.5 to 2.0 inches of excess (above average) rainfall during the months of June, July and August, the peak irrigation season. During the same period, there is a twenty five percent chance of having a rainfall deficit of 1.0 to 1.5 inches for any individual month. Frequencies for heavier one day rainfall events (0.5, 1, 2, and 3 inch quantities) were computed for the same set of climatic stations. They showed that on the average there are 4-6 one inch rainfall events per growing season, most of which occur in June, July and August. There are however a number of one inch or greater rainfall events which occur in May and September with a frequency of every two years, while similar heavy rainfalls in April and October occur with a frequency of about one year in two or three. These type of rainfalls may contribute more to leaching and runoff losses of nitrogen in the soil profile due to the absence of crop canopy that is more typical of these months. Best Management Practices (BMPs) for nitrogen in this area of the state already call for split applications to correspond more closely to crop need and uptake. This strategy alone can help compensate for the higher risk of leaching losses during these months. Precipitation events of 3 inches or greater occur across the region with a frequency of every 4-5 years and produce significant leaching losses regardless of the time of year.

Mechanical, cultural and chemical forms of weed control are used in the north-central region. The use of postemergence herbicides has been increasing in recent years, as producers have sought more flexibility in controlling weeds with a combination of methods. Late spring or early summer weed flushes missed by soil applied herbicides, cultivations or rotary hoes are often treated with specific postemergence compounds. Environmental conditions shortly before, during and after herbicide applications govern the efficacy of the compound in most cases as few herbicides are weather proof.

Spackman's method (1983) of defining spraying-occasions for herbicides was used to evaluate which of several environmental criteria were the most restrictive with respect to the use of postemergence compounds in the north-central region. Wind speed was by far the most restrictive climatic element in limiting spraying-occasions. The two wind criteria used for selecting spraying occasions were speeds less than 10 mph and speeds less than 5 mph, both of which are commonly recommended by agronomists or cited on label instructions. Using the hourly climatic records from Staples in 1994, the number of spraying occasions suitable for the use of postemergence herbicides from late May to late June were calculated. The number of spraying occasions which met the 10 mph wind speed criteria were six times more than the number which met the 5 mph criteria. This suggests opportunities to use any compounds which impose a risk associated with spray droplet or vapor drift are far fewer than for those which pose no such risk.

There are many opportunities to more fully utilize historical climatic data, soil moisture models, potential evapotranspiration estimates, weather forecast probabilities, and spraying occasion calculations in crop production mangement within the north-central region. Combined with greater utilization of soils maps and irrigation technologies, these information sources should be tested to evaluate their impact on site-specific management of irrigation water, nutrients and herbicides.

E.3 Benefits: Historical probabilities and forecast probabilities for important climatic elements can be utilized in irrigated crop production management to optimize fertilizer and herbicide usage, while minimizing the risk to the environment. Pilot testing programs which utilize these information resources can help fine-tune existing best management practices for irrigated crop production.

Detailed Reports on Activity E.3 Determine soil conditional probabilities for percolation on north-central Minnesota sandy soils. Measurements and modeling to determine soil temperature and moisture characertistics.

Contents of Detailed Reports:

E.3.1 Historical climatological distributions

E.3.2 Field measurements and models for soil temperature and moisture

E.3.3 Probability distributions of climatic variables

E.3.4 Applications of climatic data to spray occasions

E.3.1 Historical climatological distributions

Introduction: In order to examine the spatial distribution of climatic parameters, a number of long-term climatic records from communites in north-central Minnesota were studied. Based on longevity, consistency of record keeping, relative landscape position, and overall data quality, six climate stations were chosen to evaluate the spatial and temporal patterns in this region of the state: St Cloud, Wadena, Park Rapids, Long Prairie, Little Falls, and Collegeville.

In order to review the variability at each location and the spatial differences associated with standard climatic parameters, the 1948-1994 records (47 years) were used as a standard, to derive statistics for growing season length (including frost dates), as well as temperature and precipitation. These are presented in Tables E.3.1.1 through E.3.1.18.

Table E.3.1.1 Growing Season Summary for St Cloud, MN:
Elevation: 1028 ft County: Sherburne Years: 1948-1994

Base	Date of Last Spring Occurrence					Date of First Fall Occurrence				
Temp	Median	Early	90%	10%	Late	Median	Early	10%	90%	Late
32	5/12	4/20	4/26	5/26	6/01	9/24	9/01	9/17	10/07	10/28
30	5/06	4/11	4/23	5/21	5/26	9/30	9/01	9/20	10/12	10/28
28	5/01	4/07	4/19	5/16	5/23	10/05	9/03	9/24	10/20	10/31
24	4/19	3/31	4/07	5/02	5/13	10/17	9/21	9/30	11/04	11/10
20	4/07	3/19	3/24	4/20	5/04	10/31	9/22	10/11	11/11	11/19
16	3/31	2/26	3/18	4/12	4/19	11/05	10/02	10/19	11/20	11/24

Base	Length of Season (Days)				
Temp	Median	Shortest	10%	90%	Longest
32	138	99	119	157	169
30	148	118	128	166	172
28	157	120	133	182	194
24	180	140	163	199	211
20	206	167	185	219	232
16	219	177	194	243	251

Table E.3.1.2 Growing Season Summary for Wadena, MN:
Elevation: 1350 ft County: Wadena Years: 1948-1994

Base	Date of Last Spring Occurrence					Date of First Fall Occurrence				
Temp	Median	Early	90%	10%	Late	Median	Early	10%	90%	Late
32	5/12	4/22	5/02	5/25	6/01	9/24	9/07	9/13	10/05	10/08
30	5/07	4/17	4/23	5/17	5/25	9/26	9/10	9/15	10/08	10/16
28	5/03	4/11	4/19	5/14	5/21	10/03	9/12	9/20	10/16	10/27
24	4/21	3/27	4/07	5/06	5/13	10/18	9/22	10/03	10/29	11/09
20	4/12	3/24	3/30	4/28	5/03	10/27	9/26	10/11	11/11	11/19
16	4/06	3/13	3/21	4/17	4/30	11/05	10/07	10/24	11/17	11/21

Base	Length of Season (Days)				
Temp	Median	Shortest	10%	90%	Longest
32	137	103	120	151	162
30	144	113	126	161	168
28	156	114	138	169	178
24	180	139	156	197	208
20	197	170	182	216	223
16	215	185	193	233	246

Table E.3.1.3 Growing Season Summary for Park Rapids, MN:
Elevation: 1434 ft County: Hubbard Years: 1948-1994

Base	Date of Last Spring Occurrence					Date of First Fall Occurrence				
Temp	Median	Early	90%	10%	Late	Median	Early	10%	90%	Late
32	5/19	5/02	5/08	6/01	6/13	9/20	8/27	9/09	9/30	10/02
30	5/11	4/22	5/02	5/23	6/04	9/23	9/03	9/13	10/03	10/10
28	5/08	4/16	4/24	5/21	6/04	9/27	9/13	9/18	10/10	10/27
24	5/01	4/07	4/16	5/12	5/20	10/07	9/17	9/23	10/26	11/01
20	4/16	3/29	4/05	5/01	5/10	10/22	9/22	10/02	11/04	11/11
16	4/09	2/28	3/24	4/18	5/03	11/02	10/02	10/16	11/12	11/19

Base	Length of Season (Days)				
Temp	Median	Shortest	10%	90%	Longest
32	124	86	105	141	151
30	134	103	117	152	164
28	144	111	127	160	167
24	162	125	139	184	201
20	189	147	166	202	209
16	207	176	186	225	246

Table E.3.1.4 Growing Season Summary for Long Prairie, MN:
Elevation: 1290 ft County: Todd Years: 1948-1994

Base	Date of Last Spring Occurrence					Date of First Fall Occurrence				
Temp	Median	Early	90%	10%	Late	Median	Early	10%	90%	Late
32	5/16	4/15	4/26	5/27	6/21	9/22	9/01	9/11	10/03	10/10
30	5/07	4/10	4/24	5/23	6/05	9/26	9/03	9/16	10/07	10/28
28	5/01	4/10	4/21	5/15	5/20	10/01	9/12	9/20	10/16	10/29
24	4/21	3/30	4/08	5/08	5/16	10/13	9/17	9/28	10/29	11/10
20	4/11	3/21	3/30	5/01	5/12	10/29	9/22	10/13	11/12	11/19
16	4/03	3/03	3/21	4/13	4/29	11/04	10/02	10/19	11/20	11/26

Base	Length of Season (Days)				
Temp	Median	Shortest	10%	90%	Longest
32	128	101	110	150	164
30	143	103	121	159	167
28	153	125	129	177	182
24	178	139	147	193	201
20	202	152	175	220	226
16	217	189	198	235	250

Table E.3.1.5 Growing Season Summary for Little Falls, MN:
Elevation: 1120 ft County: Morrison Years: 1948-1994

Base Temp	Date of Last Spring Occurrence Median	Early	90%	10%	Late	Date of First Fall Occurrence Median	Early	10%	90%	Late
32	5/11	4/23	4/27	5/26	5/30	9/25	9/01	9/15	10/07	10/13
30	5/07	4/08	4/23	5/20	5/26	9/27	9/01	9/17	10/12	10/28
28	5/02	4/04	4/17	5/16	5/22	10/03	9/03	9/20	10/22	10/28
24	4/19	4/04	4/09	5/08	5/13	10/17	9/22	10/03	11/03	11/11
20	4/11	3/26	3/31	4/21	5/03	10/31	9/22	10/11	11/13	11/19
16	4/05	3/12	3/20	4/14	4/29	11/06	10/02	10/25	11/20	11/26

Base Temp	Length of Season (Days) Median	Shortest	10%	90%	Longest
32	137	109	120	157	164
30	147	109	126	164	177
28	158	111	130	177	191
24	181	145	153	198	212
20	201	166	183	219	234
16	215	179	199	235	248

Table E.3.1.6 Growing Season Summary for Collegville, MN:
Elevation: 1225 ft County: Stearns Years: 1948-1994

Base Temp	Date of Last Spring Occurrence Median	Early	90%	10%	Late	Date of First Fall Occurrence Median	Early	10%	90%	Late
32	5/03	4/06	4/19	5/16	5/22	10/06	9/03	9/24	10/20	10/29
30	5/01	4/05	4/16	5/09	5/22	10/10	9/21	9/28	10/26	11/04
28	4/23	4/05	4/10	5/06	5/13	10/19	9/22	10/03	10/31	11/07
24	4/11	3/23	3/31	4/29	5/04	10/29	9/26	10/18	11/11	11/19
20	4/05	3/21	3/24	4/16	5/03	11/07	10/16	10/27	11/19	11/24
16	3/29	2/26	3/18	4/10	4/26	11/10	10/17	10/30	11/24	12/04

Base Temp	Length of Season (Days) Median	Shortest	10%	90%	Longest
32	158	111	139	176	197
30	164	139	146	180	210
28	177	141	161	191	210
24	201	170	181	219	223
20	216	178	196	233	246
16	227	193	211	247	252

Table E.3.1.7 Temperature Climatology for St Cloud, MN Years: 1948-1994

Mo	Averages Max	Min	Mean	Daily Extremes High	---Date	Low	---Date	Mean Extremes High	-Yr	Low	-Yr	#Day-Max => 90	#Day-Max <= 32	#Day-Min <= 32	#Day-Min <= 0
Ja	18.6	-2.2	8.3	56	24/1981	-43	9/1977	22.3	90	-3.2	82	0.0	25.6	30.3	17.3
Fe	25.1	3.8	14.6	57	20/1981	-35	1/1951	29.2	87	4.7	89	0.0	19.2	27.3	12.1
Ma	36.8	17.0	27.1	79	30/1968	-32	1/1962	37.6	73	15.9	65	0.0	9.8	27.5	3.8
Ap	54.5	32.0	43.5	96	21/1980	-3	4/1975	51.2	77	33.6	50	0.0	0.7	16.1	0.0
Ma	68.3	43.9	56.3	97	27/1969	19	3/1967	64.6	77	50.5	54	0.4	0.0	3.0	0.0
Jn	77.1	53.2	65.4	102	24/1988	32	1/1993	71.3	88	58.7	69	1.8	0.0	0.0	0.0
Jl	82.0	58.3	70.5	102	3/1949	40	1/1969	75.0	55	63.4	92	4.0	0.0	0.0	0.0
Au	79.5	55.9	68.0	100	16/1950	33	31/1974	73.6	83	63.5	92	2.9	0.0	0.0	0.0
Se	69.2	46.0	57.9	98	7/1978	18	22/1974	64.0	48	50.5	65	0.7	0.0	1.9	0.0
Oc	57.6	35.2	46.6	90	2/1953	5	27/1976	56.7	63	40.3	76	0.0	0.2	12.5	0.0
No	38.5	20.9	29.9	74	3/1978	-20	30/1964	36.4	63	21.2	85	0.0	9.0	26.4	1.9
De	24.2	6.0	15.3	60	2/1982	-41	19/1983	26.3	59	-0.4	83	0.0	23.2	30.6	10.9
Period															
An	52.7	30.9	42.0	102	7/ 3/49	-43	1/ 9/77	46.7	87	38.1	50	9.9	87.9	175.6	46.0
Wi	22.5	2.5	12.6	60	12/ 2/82	-43	1/ 9/77	22.3	87	3.8	79	0.0	67.7	87.6	40.2
Sp	53.2	31.0	42.3	97	5/27/69	-32	3/ 1/62	50.3	77	36.0	50	0.5	10.6	46.6	3.8
Su	79.5	55.8	67.9	102	7/ 3/49	32	6/ 1/93	72.2	88	63.0	92	8.7	0.0	0.0	0.0
Fa	55.1	34.1	44.8	98	9/ 7/78	-20	11/30/64	51.6	63	40.5	76	0.7	9.3	40.7	1.9

Table E.3.1.8 Temperature Climatology for Wadena, MN Years: 1948-1994

Mo	Averages Max	Min	Mean	Daily Extremes High	---Date	Low	---Date	Mean Extremes High	-Yr	Low	-Yr	#Day-Max => 90	#Day-Max <= 32	#Day-Min <= 32	#Day-Min <= 0
Ja	16.5	-5.0	5.8	55	25/1981	-41	15/1972	18.7	90	-7.5	82	0.0	27.4	31.0	19.3
Fe	23.2	0.6	12.0	60	22/1961	-39	5/1982	26.6	87	-0.6	89	0.0	20.7	28.1	14.0
Ma	34.9	14.1	24.7	75	31/1963	-33.	10/1948	35.5	68	15.8	65	0.0	11.7	29.3	5.3
Ap	52.9	30.1	41.7	96	22/1980	-7	3/1975	50.3	55	32.6	50	0.0	1.1	19.3	0.1
Ma	67.2	42.7	55.2	96	1/1959	18	2/1967	63.9	77	47.1	79	0.2	0.0	4.0	0.0
Jn	75.2	52.7	64.1	97	6/1950	33	3/1969	69.4	88	57.9	82	1.4	0.0	0.0	0.0
Jl	80.1	57.3	69.0	101	7/1988	37	4/1972	74.1	55	60.2	92	2.8	0.0	0.0	0.0
Au	78.5	55.1	67.0	102	19/1976	36	20/1950	72.7	69	60.8	77	2.6	0.0	0.0	0.0
Se	67.8	44.9	56.6	96	8/1976	17	30/1974	62.7	48	49.5	65	0.4	0.0	2.4	0.0
Oc	56.3	33.9	45.3	94	5/1963	2	31/1951	57.0	63	38.5	76	0.0	0.4	14.3	0.0
No	36.8	19.3	28.3	74	3/1978	-22	30/1964	35.3	53	17.6	85	0.0	10.8	27.1	2.2
De	22.4	3.6	13.2	60	1/1962	-42	20/1983	25.2	59	-2.7	83	0.0	23.6	30.2	12.7
Period															
An	51.1	29.2	40.4	102	8/19/76	-42	12/20/83	46.2	63	36.4	72	7.5	95.7	185.6	53.6
Wi	20.4	-0.5	10.1	60	2/22/61	-42	12/20/83	20.4	87	-0.0	79	0.0	71.8	89.3	46.1
Sp	51.6	29.0	40.5	96	5/ 1/59	-33	3/10/48	47.1	77	34.1	79	0.3	12.8	52.5	5.4
Su	77.9	55.0	66.7	102	8/19/76	33	6/ 3/69	70.4	55	60.7	92	6.7	0.0	0.0	0.0
Fa	53.7	32.7	43.4	96	9/ 8/76	-22	11/30/64	51.3	63	38.0	93	0.5	11.2	43.9	2.2

Table E.3.1.9 Temperature Climatology for Park_Rapids, MN Years: 1948-1994

	Averages			Daily Extremes				Mean Extremes				#Day-Max		#Day-Min	
Mo	Max	Min	Mean	High	Date	Low	Date	High	Yr	Low	Yr	=> 90	<= 32	<= 32	<= 0
Ja	16.4	-6.7	4.9	51	25/1973	-45	15/1972	18.3	90	-6.3	82	0.0	27.1	30.3	19.7
Fe	24.3	-0.3	12.1	61	24/1976	-42	5/1982	25.9	87	-0.1	89	0.0	19.4	26.9	13.9
Ma	35.9	13.0	24.7	74	31/1963	-36	1/1962	36.0	73	13.5	55	0.0	10.8	28.0	6.7
Ap	53.4	28.9	41.4	96	21/1980	-8	1/1975	51.0	87	30.2	50	0.1	0.9	19.9	0.2
Ma	67.7	41.5	54.8	96	21/1964	14	1/1966	65.2	77	47.5	54	0.3	0.0	5.5	0.0
Jn	75.9	51.3	63.8	96	7/1950	28	4/1964	70.6	88	57.0	82	1.2	0.0	0.1	0.0
Jl	80.8	56.3	68.8	100	29/1975	35	4/1972	72.7	88	62.4	92	3.5	0.0	0.0	0.0
Au	79.0	54.2	66.8	101	18/1976	31	27/1982	72.1	83	60.4	77	2.9	0.0	0.0	0.0
Se	68.1	44.3	56.4	99	2/1983	17	22/1974	62.2	48	49.1	65	0.5	0.0	3.0	0.0
Oc	56.3	33.4	45.1	90	5/1963	-2	31/1951	56.3	63	39.8	52	0.0	0.5	14.6	0.0
No	36.0	18.3	27.3	72	18/1953	-29	29/1985	34.7	81	17.4	85	0.0	12.0	27.8	2.7
De	21.7	1.8	11.9	58	1/1962	-46	19/1983	22.8	59	-3.0	83	0.0	25.6	30.9	14.2
Period															
An	51.5	28.2	40.0	101	8/18/76	-46	12/19/83	45.0	87	35.7	50	8.4	96.3	187.1	57.3
Wi	20.6	-1.9	9.5	61	2/24/76	-46	12/19/83	19.4	87	1.8	79	0.0	71.7	87.5	47.6
Sp	52.3	27.8	40.3	96	5/21/64	-36	3/ 1/62	48.9	77	32.9	50	0.3	11.7	53.4	6.9
Su	78.6	53.9	66.5	101	8/18/76	28	6/ 4/64	70.9	88	62.3	92	7.6	0.0	0.1	0.0
Fa	53.5	32.0	43.0	99	9/ 2/83	-29	11/29/85	50.3	63	38.0	51	0.5	12.5	45.4	2.7

Table E.3.1.10 Temperature Climatology for Long_Prairie, MN Years: 1948-1994

	Averages			Daily Extremes				Mean Extremes				#Day-Max		#Day-Min	
Mo	Max	Min	Mean	High	Date	Low	Date	High	Yr	Low	Yr	=> 90	<= 32	<= 32	<= 0
Ja	18.3	-2.6	8.0	56	24/1981	-40	21/1954	23.3	90	-3.3	82	0.0	25.6	30.3	17.4
Fe	25.3	2.8	14.3	59	17/1981	-42	1/1951	29.8	87	4.9	79	0.0	18.7	27.3	12.4
Ma	36.7	16.0	26.6	74	30/1968	-35	1/1962	37.4	73	14.9	65	0.0	10.0	27.7	4.8
Ap	54.6	31.7	43.4	95	21/1980	-7	4/1975	53.2	87	31.6	50	0.0	0.8	16.4	0.1
Ma	69.0	43.9	56.6	95	2/1959	19	4/1967	65.6	88	49.7	67	0.4	0.0	3.6	0.0
Jn	77.4	53.4	65.6	100	14/1979	30	4/1964	73.7	88	58.5	58	1.8	0.0	0.0	0.0
Jl	82.3	58.0	70.4	103	6/1988	35	4/1967	76.4	88	64.0	92	4.5	0.0	0.0	0.0
Au	80.1	55.8	68.2	102	1/1988	33	25/1950	72.9	83	63.1	50	3.3	0.0	0.0	0.0
Se	70.1	46.1	58.3	95	5/1960	19	22/1974	63.4	48	50.4	65	0.5	0.0	2.2	0.0
Oc	58.4	35.5	47.2	90	2/1953	3	31/1951	57.0	63	40.9	76	0.0	0.2	12.2	0.0
No	38.3	20.9	29.9	73	2/1978	-23	30/1964	36.7	81	20.0	51	0.0	9.1	26.2	1.8
De	23.7	5.6	14.8	59	1/1962	-39	19/1983	25.5	59	0.7	83	0.0	23.1	30.8	11.5
Period															
An	52.8	30.5	41.9	103	7/ 6/88	-42	2/ 1/51	48.3	87	34.0	49	10.5	87.5	176.7	48.1
Wi	22.3	1.9	12.2	59	12/ 1/62	-42	2/ 1/51	23.8	87	4.6	79	0.0	67.0	87.7	41.3
Sp	53.5	30.5	42.2	95	5/ 2/59	-35	3/ 1/62	50.8	87	34.3	50	0.4	10.9	47.7	5.0
Su	79.9	55.7	68.1	103	7/ 6/88	30	6/ 4/64	74.2	88	63.9	58	9.6	0.0	0.0	0.0
Fa	55.7	34.3	45.2	95	9/ 5/60	-23	11/30/64	51.5	63	39.8	51	0.5	9.3	40.7	1.8

Table E.3.1.11 Temperature Climatology for Little_Falls, MN Years: 1948-1994

	Averages			Daily Extremes				Mean Extremes				#Day-Max		#Day-Min	
Mo	Max	Min	Mean	High	Date	Low	Date	High	Yr	Low	Yr	=> 90	<= 32	<= 32	<= 0
Ja	19.4	-2.5	8.6	54	24/1981	-41	9/1977	23.1	90	-2.1	66	0.0	26.2	30.9	17.8
Fe	26.3	3.1	14.9	58	22/1961	-37	8/1971	29.2	87	4.9	67	0.0	18.6	28.0	12.2
Ma	38.2	16.2	27.5	75	30/1968	-39	1/1962	37.4	73	14.1	65	0.0	8.3	28.4	4.6
Ap	56.3	31.6	44.2	95	21/1980	-5	1/1975	52.8	87	34.9	50	0.0	0.4	16.6	0.1
Ma	70.5	43.9	57.5	95	3/1949	18	1/1966	67.5	77	50.8	67	0.5	0.0	3.2	0.0
Jn	78.6	53.6	66.3	99	19/1988	34	4/1951	73.2	88	59.5	69	2.0	0.0	0.0	0.0
Jl	83.3	58.6	71.1	102	6/1988	39	1/1969	77.3	88	64.1	92	5.1	0.0	0.0	0.0
Au	80.9	56.2	68.8	101	18/1976	36	20/1950	74.4	83	64.9	51	3.6	0.0	0.0	0.0
Se	71.0	46.7	59.1	99	7/1978	17	22/1974	64.9	48	50.0	65	0.7	0.0	1.7	0.0
Oc	59.2	36.0	47.8	91	2/1953	5	31/1951	57.3	63	41.7	76	0.0	0.1	11.3	0.0
No	39.2	21.6	30.7	75	3/1978	-24	30/1964	37.4	81	21.5	85	0.0	8.2	25.5	1.6
De	24.7	5.8	15.4	60	1/1962	-42	19/1983	25.6	59	0.8	83	0.0	22.2	30.3	11.0
Period															
An	54.1	31.1	42.8	102	7/ 6/88	-42	12/19/83	48.3	87	40.0	65	12.0	83.9	175.9	47.3
Wi	23.3	2.0	12.8	60	12/ 1/62	-42	12/19/83	22.8	87	5.3	79	0.0	67.2	89.2	41.1
Sp	55.0	30.6	43.0	95	5/ 3/49	-39	3/ 1/62	51.7	77	37.5	65	0.5	8.6	48.2	4.7
Su	80.9	56.2	68.8	102	7/ 6/88	34	6/ 4/51	74.1	88	64.6	92	10.7	0.0	0.0	0.0
Fa	56.5	34.8	45.9	99	9/ 7/78	-24	11/30/64	51.5	63	41.3	59	0.7	8.3	38.4	1.6

Table E.3.1.12 Temperature Climatology for Collegeville, MN Years: 1948-1994

	Averages			Daily Extremes				Mean Extremes				#Day-Max		#Day-Min	
Mo	Max	Min	Mean	High	Date	Low	Date	High	Yr	Low	Yr	=> 90	<= 32	<= 32	<= 0
Ja	19.2	0.6	10.0	54	24/1981	-36	9/1977	24.7	90	-1.3	77	0.0	25.2	30.1	15.3
Fe	25.7	6.7	16.4	60	23/1951	-30	5/1982	31.2	87	6.6	67	0.0	18.2	26.7	9.8
Ma	37.1	18.8	28.2	77	30/1968	-30	1/1962	38.0	73	17.0	65	0.0	9.6	26.7	3.0
Ap	54.9	34.0	44.6	95	21/1980	2	4/1975	54.4	87	34.2	50	0.0	0.6	13.7	0.0
Ma	69.3	46.5	58.2	96	27/1969	19	3/1967	66.7	77	51.1	54	0.3	0.0	1.5	0.0
Jn	77.6	55.9	67.0	101	24/1988	35	2/1964	74.7	88	59.9	69	1.7	0.0	0.0	0.0
Jl	82.1	60.9	71.8	103	31/1988	41	1/1969	77.5	88	65.9	92	3.8	0.0	0.0	0.0
Au	79.6	58.9	69.5	100	1/1988	39	28/1965	75.9	83	65.2	51	2.6	0.0	0.0	0.0
Se	69.7	49.4	59.8	97	15/1948	23	26/1965	65.9	48	50.9	65	0.5	0.0	0.4	0.0
Oc	58.3	38.6	48.7	89	2/1953	13	31/1951	58.1	63	42.2	59	0.0	0.2	7.8	0.0
No	38.8	23.6	31.4	74	3/1978	-19	30/1964	37.7	81	22.5	85	0.0	8.7	24.1	1.2
De	24.6	8.4	16.7	58	2/1982	-35	19/1983	27.0	59	2.2	83	0.0	22.1	30.3	9.1
Period															
An	53.3	33.7	43.7	103	7/31/88	-36	1/ 9/77	49.4	87	40.3	51	8.9	84.6	161.3	38.5
Wi	23.0	5.1	14.2	60	2/23/51	-36	1/ 9/77	24.9	87	6.0	79	0.0	65.1	86.5	34.3
Sp	53.8	33.1	43.6	96	5/27/69	-30	3/ 1/62	51.7	87	37.1	50	0.4	10.2	41.9	3.0
Su	79.8	58.6	69.4	103	7/31/88	35	6/ 2/64	75.0	88	65.5	92	8.1	0.0	0.0	0.0
Fa	55.8	37.2	46.8	97	9/15/48	-19	11/30/64	52.9	63	41.9	59	0.5	8.9	32.3	1.2

Table E.3.1.13 Precipitation Climatology for St Cloud, MN Years: 1948-1994

Mo	Total Precipitation Mean	High	Yr	Low	Yr	1-Day Max	Date	Snow Mean	Snow High	Yr	#Days Precip =>.10	=>.50	=>1.
Ja	0.77	2.52	69	0.06	90	0.60	10/1975	9.9	29.9	75	2.5	0.1	0.0
Fe	0.68	2.76	51	0.04	64	1.81	28/1951	7.2	21.6	71	1.9	0.2	0.0
Ma	1.39	3.43	65	0.10	59	1.13	11/1977	9.4	51.7	65	3.9	0.7	0.1
Ap	2.32	5.55	86	0.05	87	2.47	26/1984	2.9	11.1	50	5.2	1.6	0.3
Ma	3.24	8.01	62	0.82	67	3.22	9/1979	0.1	3.2	71	6.7	2.0	0.5
Jn	4.71	10.52	90	0.05	88	3.46	26/1983	0.0	0.0	0	7.4	3.0	1.3
Jl	3.26	8.00	55	0.21	75	2.29	22/1972	0.0	0.0	0	6.2	2.5	0.7
Au	4.04	7.55	56	0.46	50	4.57	3/1956	0.0	0.0	0	6.2	2.6	1.3
Se	2.86	9.48	85	0.07	52	3.62	8/1985	0.0	0.0	0	5.6	2.0	0.6
Oc	2.00	6.16	71	0.07	52	3.21	1/1950	0.5	4.1	59	3.9	1.1	0.5
No	1.30	3.74	77	0.14	67	2.02	9/1977	6.9	25.0	83	3.3	0.7	0.1
De	0.82	2.04	69	0.13	52	0.69	15/1984	8.2	25.4	68	2.4	0.2	0.0
Period													
An	27.50	39.34	65	14.93	76	4.57	8/ 3/56	45.2	81.7	65	55.8	17.0	5.5
Wi	2.27	5.16	69	0.86	87	1.81	2/28/51	25.3	55.1	69	6.9	0.5	0.0
Sp	6.94	13.66	65	2.26	67	3.22	5/ 9/79	12.4	57.8	65	15.7	4.3	0.9
Su	12.05	19.05	90	3.51	50	4.57	8/ 3/56	0.0	0.0	0	20.1	8.2	3.4
Fa	6.17	12.75	83	0.61	52	3.62	9/ 8/85	7.2	25.7	83	12.8	3.8	1.2

Table E.3.1.14 Precipitation Climatology for Wadena, MN Years: 1948-1994

Mo	Total Precipitation Mean	High	Yr	Low	Yr	1-Day Max	Date	Snow Mean	Snow High	Yr	#Days Precip =>.10	=>.50	=>1.
Ja	0.85	2.47	69	0.06	57	1.31	4/1949	10.8	30.8	50	2.9	0.2	0.0
Fe	0.58	1.66	79	0.02	58	1.03	20/1954	7.0	23.7	79	1.7	0.2	0.0
Ma	1.44	3.84	66	0.10	59	1.95	15/1957	10.0	36.3	66	3.6	0.7	0.1
Ap	2.45	5.12	68	0.05	80	2.30	24/1960	4.7	24.0	50	5.6	1.6	0.4
Ma	3.09	8.90	65	0.37	48	2.92	12/1985	0.3	5.7	54	6.0	2.1	0.6
Jn	4.28	10.46	68	0.96	87	3.03	10/1968	0.0	0.0	0	7.9	3.0	1.2
Jl	3.73	7.48	59	0.81	67	4.33	8/1959	0.0	0.0	0	6.6	2.4	1.0
Au	3.29	8.40	53	0.24	70	5.25	26/1955	0.0	0.0	0	5.6	2.0	0.8
Se	2.49	7.63	65	0.24	74	3.23	12/1980	0.0	0.3	65	5.3	1.5	0.4
Oc	1.96	8.47	84	0.16	76	3.91	15/1984	1.1	11.9	51	3.8	1.2	0.3
No	1.26	3.58	77	0.11	67	1.73	9/1977	6.8	25.5	93	3.2	0.7	0.1
De	0.81	2.72	51	0.07	75	1.25	3/1951	7.7	25.8	68	2.6	0.3	0.0
Period													
An	26.24	38.00	65	13.42	76	5.25	8/26/55	48.4	102.0	50	54.8	15.9	5.1
Wi	2.25	5.49	69	0.69	87	1.31	1/ 4/49	25.6	62.2	69	7.2	0.7	0.1
Sp	6.98	14.79	65	2.25	52	2.92	5/12/85	14.9	56.5	66	15.2	4.5	1.1
Su	11.30	18.16	53	5.91	50	5.25	8/26/55	0.0	0.0	0	20.1	7.3	3.0
Fa	5.71	11.44	77	1.05	52	3.91	10/15/84	7.9	25.5	93	12.3	3.4	0.9

Table E.3.1.15 Precipitation Climatology for Park Rapids, MN Years: 1948-1994

Mo	Total Precipitation Mean	High	Yr	Low	Yr	1-Day Max	Date	Snow Mean	Snow High	Yr	#Days Precip =>.10	=>.50	=>1.
Ja	0.74	2.90	50	0.05	81	0.61	12/1988	10.6	32.4	69	2.9	0.2	0.0
Fe	0.49	1.62	79	0.01	58	0.73	24/1977	6.3	24.1	79	1.8	0.1	0.0
Ma	1.16	3.26	66	0.14	69	1.50	27/1950	10.2	41.4	66	3.6	0.4	0.0
Ap	2.23	5.85	70	0.19	87	2.24	28/1970	5.2	20.0	66	5.0	1.4	0.4
Ma	2.96	7.66	62	0.20	76	3.49	29/1953	0.4	10.0	54	6.4	1.9	0.5
Jn	4.24	8.97	94	0.82	61	4.03	20/1994	0.0	0.0	0	7.7	3.2	1.0
Jl	4.00	11.60	49	0.42	67	6.08	18/1985	0.0	0.0	0	6.7	2.3	0.9
Au	3.82	9.53	89	0.34	69	5.37	6/1986	0.0	0.0	0	6.0	2.3	1.0
Se	2.65	6.54	61	0.20	52	2.96	4/1971	0.0	0.0	0	5.4	1.8	0.6
Oc	2.06	6.54	71	0.18	92	4.57	10/1973	1.0	9.0	70	4.0	1.2	0.4
No	1.03	2.73	77	0.11	72	1.39	1/1974	5.7	24.0	93	2.7	0.5	0.1
De	0.80	2.61	51	0.14	75	1.43	6/1987	8.5	26.8	68	2.6	0.2	0.0
Period													
An	26.13	40.51	85	12.53	76	6.08	7/18/85	46.7	90.9	66	55.0	15.6	5.0
Wi	2.04	4.96	69	0.79	63	1.43	12/ 6/87	25.1	66.9	69	7.3	0.5	0.0
Sp	6.28	11.23	62	2.00	80	3.49	5/29/53	16.1	61.4	66	15.1	3.7	0.9
Su	12.09	23.45	85	5.93	70	6.08	7/18/85	0.0	0.0	0	20.7	7.9	3.0
Fa	5.70	12.28	71	1.38	52	4.57	10/10/73	6.7	24.8	93	12.2	3.6	1.1

Table E.3.1.16 Precipitation Climatology for Long Prairie, MN Years: 1948-1994

Mo	Total Precipitation Mean	High	Yr	Low	Yr	1-Day Max	Date	Snow Mean	Snow High	Yr	#Days Precip =>.10	=>.50	=>1.
Ja	1.00	3.39	69	0.03	61	1.20	4/1949	10.5	29.1	75	3.0	0.3	0.0
Fe	0.76	1.99	81	0.00	64	1.08	28/1981	7.5	21.1	79	2.2	0.3	0.0
Ma	1.68	4.43	65	0.03	59	1.65	4/1985	9.2	32.5	65	4.2	0.9	0.2
Ap	2.37	6.16	86	0.00	49	2.06	26/1994	3.1	23.0	50	5.6	1.5	0.3
Ma	3.11	9.38	59	0.27	76	3.00	31/1959	0.1	2.3	54	6.4	1.9	0.7
Jn	4.08	10.64	53	0.70	59	3.23	19/1953	0.0	0.0	0	7.5	2.7	1.0
Jl	3.73	15.55	72	0.58	67	8.90	22/1972	0.0	0.0	0	6.7	2.3	1.0
Au	3.53	7.19	73	0.34	76	4.52	26/1955	0.0	0.0	0	5.7	2.5	0.9
Se	2.63	6.56	86	0.24	52	2.64	4/1989	0.0	0.0	0	4.9	1.7	0.6
Oc	2.03	8.38	71	0.07	52	2.49	31/1979	0.8	7.0	51	4.1	1.2	0.5
No	1.34	4.00	77	0.06	67	1.61	9/1977	6.5	23.8	93	3.2	0.8	0.2
De	0.92	2.83	68	0.08	58	0.92	4/1955	8.4	26.8	68	2.9	0.3	0.0
Period													
An	27.04	44.60	72	14.03	76	8.90	7/22/72	45.9	82.7	51	56.3	16.3	5.5
Wi	2.64	7.18	69	0.43	63	1.20	1/ 4/49	27.3	55.4	69	8.2	1.0	0.1
Sp	7.24	13.03	65	3.20	67	3.00	5/31/59	12.7	33.5	51	16.4	4.4	1.3
Su	11.39	24.82	72	5.26	50	8.90	7/22/72	0.0	0.0	0	20.2	7.6	3.0
Fa	6.06	13.57	71	0.87	52	2.64	9/ 4/89	7.5	23.8	93	12.3	3.7	1.3

Table E.3.1.17 Precipitation Climatology for Little Falls, MN Years: 1948-1994

Mo	Total Precipitation Mean	High	Yr	Low	Yr	1-Day Max		Snow Mean	Snow High	Yr	#Days Precip =>.10	=>.50	=>1.
Ja	0.68	2.93	75	0.00	74	1.20	11/1975	9.8	36.5	75	2.3	0.1	0.0
Fe	0.55	2.10	52	0.00	58	0.92	19/1952	7.1	25.1	71	1.8	0.2	0.0
Ma	1.33	4.22	90	0.08	59	1.64	12/1977	8.7	41.5	65	3.7	0.7	0.1
Ap	2.13	5.65	86	0.00	87	2.02	26/1954	2.0	8.0	94	5.0	1.4	0.4
Ma	3.02	7.71	59	0.75	67	2.30	22/1962	0.0	2.0	71	6.7	1.9	0.6
Jn	4.30	8.42	68	0.73	87	3.28	2/1949	0.0	0.0	0	7.9	2.8	1.1
Jl	3.75	9.61	72	0.65	76	4.55	22/1972	0.0	0.0	0	6.6	2.6	1.0
Au	3.79	9.10	53	0.20	76	4.70	1/1953	0.0	0.0	0	5.8	2.5	1.2
Se	2.56	6.25	65	0.30	52	2.05	18/1950	0.0	0.0	0	5.4	1.7	0.6
Oc	2.10	9.52	71	0.01	52	3.10	6/1982	0.7	6.0	87	3.9	1.1	0.6
No	1.20	3.78	77	0.04	84	2.50	9/1977	6.0	24.0	88	3.1	0.6	0.2
De	0.68	2.71	68	0.00	58	1.10	8/1963	8.0	31.0	68	2.5	0.2	0.0
Period													
An	25.96	36.57	65	13.38	76	4.70	8/ 1/53	41.2	78.5	75	54.3	15.9	5.8
Wi	1.86	5.78	69	0.40	87	1.20	1/11/75	24.8	64.1	69	6.7	0.6	0.0
Sp	6.44	11.48	91	2.38	80	2.30	5/22/62	10.7	48.5	65	15.9	4.2	1.1
Su	11.84	19.95	52	3.58	50	4.70	8/ 1/53	0.0	0.0	0	20.3	7.9	3.3
Fa	5.89	13.12	71	0.76	52	3.10	10/ 6/82	6.5	24.5	91	12.6	3.5	1.3

Table E.3.1.18 Precipitation Climatology for Collegeville, MN Years: 1948-1994

Mo	Total Precipitation Mean	High	Yr	Low	Yr	1-Day Max		Snow Mean	Snow High	Yr	#Days Precip =>.10	=>.50	=>1.
Ja	0.88	2.99	75	0.02	90	1.26	4/1949	10.5	32.9	75	2.5	0.2	0.0
Fe	0.74	3.21	71	0.05	58	1.61	26/1971	8.0	26.5	71	2.0	0.2	0.0
Ma	1.60	5.53	65	0.10	59	1.80	1/1965	10.4	66.4	65	3.7	1.0	0.2
Ap	2.33	6.30	86	0.04	87	2.83	26/1954	3.0	13.7	91	5.0	1.5	0.4
Ma	3.48	8.95	62	0.58	76	5.84	22/1962	0.1	2.3	71	6.7	2.3	0.7
Jn	4.59	11.19	53	0.16	88	3.54	17/1957	0.0	0.0	0	7.6	2.9	1.2
Jl	3.27	7.85	72	0.43	67	2.93	18/1986	0.0	0.0	0	6.6	2.2	0.7
Au	4.00	8.22	56	0.38	50	4.18	31/1977	0.0	0.0	0	6.5	2.7	1.1
Se	3.16	7.82	86	0.27	52	3.10	8/1991	0.0	0.0	0	5.9	2.1	0.7
Oc	2.17	7.84	71	0.05	52	1.97	16/1968	0.4	3.9	69	4.0	1.4	0.5
No	1.41	4.30	77	0.06	80	2.68	9/1977	7.3	26.6	83	3.2	0.9	0.2
De	0.81	2.55	68	0.03	58	1.30	8/1963	8.7	34.0	68	2.4	0.3	0.0
Period													
An	28.45	44.95	77	16.44	76	5.84	5/22/62	47.9	98.1	65	56.7	17.9	6.0
Wi	2.44	5.93	69	0.64	87	1.61	2/26/71	27.2	65.9	69	6.9	0.7	0.1
Sp	7.40	16.04	65	2.30	67	5.84	5/22/62	13.2	68.3	65	15.5	4.8	1.3
Su	11.85	19.09	86	3.19	50	4.18	8/31/77	0.0	0.0	0	20.9	7.9	3.1
Fa	6.75	13.42	71	1.29	52	3.10	9/ 8/91	7.8	27.9	91	13.1	4.3	1.4

Results: Examination of Tables E.3.1.1 through E.3.1.6 shows that the median length of the frost free growing season ranges from 124 days at Park Rapids to 158 days at Collegeville. This is primarily due to latitudinal position, as the south-north distance between these two sites is about 150 miles. Due to occasional June and August frosts, growing seasons have been as short as 86 days at Park Rapids, yet they have also been as long as 151 days, a difference of 65 days. At Collegeville, length of frost free growing season has ranged from 111 days to 197 days, a range of 86 days.

With the exception of Park Rapids (late August), all climate stations show some incidence of fall frosts in the first or second week of September, some with a frequency of ten percent of the years. This year to year, or temporal variability is greater than the spatial variability across the region and at least partially contributes to the desire to plant early when possible.

Tables E.3.1.7 through E.3.1.12 show the temperature climatology for the six north central climate stations. Collegeville is the warmest and Park Rapids the coolest in terms of average annual temperature. Since 1948, extreme maximum temperatures have been 103 degrees F at Long Prairie and Collegeville, while the extreme minimum has been -46 degrees F at Park Rapids. The average number of days per year with maximum temperatures of 90 degrees F or above range from 7.5 at Wadena to 12 at Little Falls. Year to year variability is illustrated by the range in mean monthly temperatures shown in the tables. For example, the mean temperature in July during the peak of the irrigation season has ranged from 60.2 degrees F (1992) to 74.1 degrees F (1955) at Wadena, nearly a 14 degree F difference. It is easy to see that the irrigation need of any one growing season might be less than half of that of another growing season. The most extreme conditions of temperature could not be managed even with the best of irrigation systems because most design capacities could not keep up with the accompanying high values of daily evapotranspiration.

Tables E.3.1.13 through E.3.1.18 show the precipitation climatology for the six north central climate stations. The driest location is Little Falls, with average annual precipitation of 25.96 inches, while the wettest location is Collegeville with 28.45 inches. Once again the year to year variability is illustrated by some of the extreme ranges of individual months, most notably June, July and August. For example, July rainfall at Long Prairie has ranged from 0.58 inches in 1967 to 15.55 inches in 1972.

Excessive one day rainfall events can greatly exacerbate even the best irrigation practices, causing excessive nutrient losses by runoff and leaching. One day rainfall events have ranged from 4.57 inches at St Cloud (August) to 8.90 inches at Long Prairie (July). All locations have had rainfalls in excess of 4 inches primarily in July and August, although some have had such rains in June and May as well. Across the region, rainfalls of 1 inch or greater occur with a frequency of 4-6 times per year.

Summary: Simple climatic statistics were derived for six stations in the north-central sands region of Minnesota. Length of the growing season, as well as temperature and precipitation characteristics were examined. Though a certain degree of spatial variability was exhibited among the six locations, the temporal or year to year variability was much greater with respect to these climatic parameters. It is unlikely that the impact of extreme climatic events noted in the historical records could be mitigated by best management irrigation practices.

E.3.2 Measurements and models for soil temperature and moisture

Introduction: Soil temperature and moisture records in the north-central region are few and far between, yet these climatic parameters are important to the understanding of mineralization rates of nitrogen, as well as the losses of nitrates from the soil by runoff and leaching. Mineralization rates will typically increase above 50 degrees F and peak in the 60 to 70 degrees F range if adequate soil moisture is present. Leaching and runoff losses of nitrate from the soil are primarily rainfall driven but conditioned by the soil moisture status of the soil, that is its capacity to hold additional moisture.

The best soil temperature records in the region come from the Staples Irrigation Center, which monitors two depths on a daily basis, 4 inch depth and 8 inch depth. These measurements extend back to 1983 and were used to examine the average temporal pattern and variability in soil temperature during the growing season.

No historical time series of soil moisture measurements was found for the north-central sands. Using the CERES-Maize model of corn growth and development published by Jones and Kiniry (1986), a submodel to produce soil moisture estimates for each day was run on multiple station climatic records (1951-1993). The resulting 43 year record of daily soil moisture estimates was used to derive the temporal distribution characteristics for a 60 inch rootzone. The model was run using the water holding characteristics for a Verndale sandy loam soil series, one typical of this region of the state.

Results: Figures E.3.1 and E.3.2 shows the temporal pattern for average four and eight inch depth soil temperatures and their variability from early April (week 17) to early November (week 44) at Staples, MN. The temporal pattern in both the four inch and eight inch depth shows considerable variability in the early spring and fall periods, with lesser variability during the summer months. Average temperatures at a depth of four inches reach 50 degrees F or greater during the last week of April. Average soil temperatures at the eight inch depth reach 50 degrees F about 1 to 2 weeks later. Thus, it might be expected that more active mineralization rates from nitrogen sources in the soil would begin to occur about this time, just ahead of the usual planting time in the region. Best Management Practices (BMPs) for nitrogen fertilizer in the area stress the need to split applications such that they are timed to crop need and minimize residence time in the soil profile from which they might be leached by excessive rainfall, or unexpected rainfall in combination with irrigation. However, manure applications may be made at other times of year and in large enough quantities that they would be subject to a higher degree of variability in soil temperature (and therefore mineralization), as well as soil moisture and rainfall which might produce runoff and leaching losses of nitrate.

Based on the seasonal trend in both four inch and eight inch soil temperatures, peak mineralization rates within the soil rootzone would be expected to persist from mid June to late August, when mean soil temperatures are consistently above 70 degrees F. Manure applied to the soil after October 10 would be subject to little mineralization in most years, as soil temperatures decline below 50 degrees F. Average soil freezup is on or about November 25 at which point most biological and chemical activity within the soil all but cease for the winter.

The degree to which soil temperatures are moderated by irrigation is unknown on these soils, but may be useful to investigate in order to fine-tune site specific management of fertilizer and manure applications which supply nitrogen sources subject to mineralization rates highly regulated by a variable soil environment. In addition more soil temperature records in different soil series across the region would be useful to assess the degree of regional variability in this parameter.

Soil moisture retention in the north-central sands is generally poor, especially in the near surface layers. Volumetric field capacity for soil moisture in many of these sandy soils ranges from 15 to 18 percent, while volumetric wilting point moisture content ranges from 6 to 8 percent. This equates to an available water holding capacity ranging from only 1.0 to 1.3 inches per foot of soil. Irrigation is used extensively on these soils when producing crops which have high water requirements such as corn and potatoes.

Volumetric soil moisture estimates were derived for a Verndale sandy loam soil series using the CERES-Maize computer model described by Jones and Kiniry (1986). A 60 inch rootzone was assumed with an available water holding capacity of 1.08 inches/foot of soil, based on volumetric estimates of field capacity and permanent wilting point. Data from the six north-central climate stations, covering the period 1951-1993 were used to derive daily estimates of plant available moisture.

Because of uncertainty about soil moisture estimates during the frozen period of winter, only the temporal pattern in soil moisture during the crop growing season was examined. Table E.3.19 summarizes the frequency distribution of soil moisture values. The percentage of time soil moisture exceeds 0, 20, 50, 80, and 100 percent of available capacity is noted weekly from April 8 to November 4.

The temporal distribution of soil moisture in the region shows that beginning in mid July and lasting well into September, soil moisture levels in the top 60 inches are at their lowest levels. In fact over a quarter of the time during late July and early August, available soil moisture values are less than 20 percent. This corresponds to the peak irrigation season for most crops in the region when rainfed soil moisture is supplemented heavily by overhead sprinkler applications.

Many irrigators in the north central sands use estimates of potential evapotranspiration on a daily basis coupled with monitoring soil moisture levels to help schedule irrigations during the crop season. However, little use is made of historical patterns of potential evapotranspiration and temporal soil moisture probabilities to critically look at irrigation design capacities. Such historical information could be helpful in designing systems to accommodate the most extreme of soil moisture conditions when they do occur.

In addition, weather forecast probabilities are under-utilized in making decisions about when to apply irrigation as well as how much to apply. Probability of precipitation forecasts (POPs) and quantified precipitation forecasts (QPF) are available daily from the National Weather Service Forecast Offices in Minnesota, but are rarely used in irrigation decisions. Utilizing these information resources more fully should improve site-specific management of irrigation systems on the soils of north-central Minnesota. A pilot effort with some members of the North-Central Irrigators Association has been initiated to test this hypothesis.

Summary: Temporal patterns in soil temperature and estimated soil moisture levels derived for the north-central sands show variability characteristics which might be of value in planning fertility and irrigation strategies in order to better time applications of nutrients and water. Irrigators are being encouraged to utilize some of these data in evaluating their present management techniques. Pilot programs are also underway to make greater utilization of real-time weather data and forecasted probabilities as well. Use of this type of information might not only improve efficiency of inputs (water and nutrients) but also reduce the risk of leaching and runoff events.

Table E.3.19 Frequency distribution of soil moisture values (60 inch rootzone) related to available water holding capacity throughout the growing season in north-central Minnesota (1951-1993) as estimated by CERES-Maize. Numbers are percentage of years at or above the given level of available moisture.

	Frequency of Exceedance Percent of Available Capacity				
Week Ending	100%	80%	50%	20%	0%
Apr 8	47	87	92	99	100
Apr 15	47	86	92	99	100
Apr 22	50	88	93	97	100
Apr 29	50	89	93	98	100
May 6	60	88	94	100	100
May 13	74	90	95	98	100
May 20	82	91	95	100	100
May 27	83	91	96	100	100
Jun 3	86	92	97	100	100
Jun 10	78	90	95	100	100
Jun 17	69	91	95	100	100
Jun 24	61	90	95	100	100
Jul 1	54	80	91	100	100
Jul 8	47	71	83	98	100
Jul 15	44	65	76	90	100
Jul 22	42	57	67	85	100
Jul 29	36	52	62	83	100
Aug 5	37	45	59	74	100
Aug 12	34	45	54	74	100
Aug 19	29	39	52	74	96
Aug 26	25	40	54	74	100
Sep 2	24	43	65	79	99
Sep 9	24	46	66	79	100
Sep 16	24	41	64	94	100
Sep 23	30	47	64	98	100
Sept 30	27	47	70	96	100
Oct 7	25	48	76	96	100
Oct 14	28	48	80	99	100
Oct 21	28	47	85	99	100
Oct 28	28	48	86	99	100
Nov 4	27	53	91	100	100

E.3.3 Probability distributions of climatic variables

Introduction: Simple climatic probabilities for monthly precipitation and daily maximum and minimum temperature were examined. The distributional characteristics of these simple parameters provide some measure of the limits of extreme conditions encountered in managing plant nutrients and irrigation in the north-central sands of Minnesota.

Results: Tables E.3.20 through E.3.25 shows the probability distributions for monthly precipitation at the six climate stations in the region. For each location there is a 25 percent probability of having a monthly precipitation deficit of 1.0 to 1.5 inches during the growing season. On the other hand, there is a 10 percent probability of having a monthly precipitation value that is twice normal (50 pct probability level). Extremes of 10 inches or greater have only occurred in the months of June, July and August, while each of those months also has a 1 to 5 percent probability of receiving less than 1 inch of rainfall.

Table E.3.26 summarizes the frequency distribution of rainfall events based on inferred intensity. The number of 24 hr rainfall events greater than 0.5, 1.0, 2.0, and 3.0 inches were examined for each of the six climate stations over the period 1948-1994. This was done to study the temporal distribution of such events across the crop growing season. The highest frequency of these heavier rainfall amounts is consistently in the months of June, July and August, representing between 60 and 65 percent of the distribution. Two and three inch rainfalls are increasingly concentrated in these months.

On the average there are 4-6 one inch rainfall events per growing season, though May, September and October show more than a few occurrences of two inch rainfalls. These type of rainfalls may contribute more to leaching and runoff losses of nitrogen in the soil profile due to the absence of crop canopy. Fortunately, crop canopies are usually maximum during the months when heavier rains are more frequent. Best Management Practices (BMPs) for nitrogen in this area of the state already call for split applications to correspond more closely to crop need and uptake. This strategy alone can help compensate for the higher risk of leaching losses during the summer months. Precipitation events of 3 inches or greater occur across the region with a frequency of about every 4 years and produce significant leaching losses regardless of the time of year.

Table E.3.20 Monthly probability distributions for precipitation at St Cloud, MN (1948-1994) Probability (pct) and Precipitation (in)

MO	1%	5%	10%	25%	50%	75%	90%	95%	99%
Ja	0.06	0.14	0.20	0.37	0.65	1.04	1.50	1.83	2.57
Fe	0.03	0.09	0.14	0.29	0.54	0.93	1.40	1.74	2.50
Ma	0.20	0.38	0.51	0.80	1.23	1.81	2.46	2.92	3.90
Ap	0.20	0.46	0.67	1.17	1.98	3.10	4.42	5.35	7.41
Ma	0.71	1.16	1.46	2.09	2.99	4.12	5.34	6.17	7.94
Jn	0.53	1.09	1.53	2.53	4.11	6.24	8.69	10.41	14.17
Ju	0.54	0.96	1.27	1.94	2.94	4.23	5.67	6.67	8.81
Au	0.85	1.40	1.78	2.58	3.71	5.14	6.70	7.77	10.04
Se	0.33	0.67	0.94	1.55	2.50	3.79	5.27	6.30	8.57
Oc	0.07	0.20	0.34	0.75	1.54	2.76	4.28	5.41	8.01
No	0.08	0.21	0.32	0.60	1.08	1.76	2.58	3.16	4.46
De	0.07	0.16	0.24	0.41	0.70	1.09	1.55	1.88	2.60
Period									
An	15.82	18.70	20.37	23.39	27.09	31.16	35.15	37.69	42.76
Wi	0.62	0.93	1.14	1.56	2.14	2.84	3.59	4.10	5.17
Sp	2.43	3.37	3.96	5.11	6.64	8.45	10.32	11.57	14.15
Su	5.39	6.90	7.82	9.53	11.71	14.20	16.71	18.35	21.69
Fa	1.35	2.19	2.77	3.98	5.69	7.84	10.18	11.77	15.17

Table E.3.21 Monthly probability distributions for precipitation at Wadena, MN (1948-1994) Probability (pct) and Precipitation (in)

MO	1%	5%	10%	25%	50%	75%	90%	95%	99%
Ja	0.04	0.11	0.18	0.37	0.69	1.16	1.74	2.16	3.10
Fe	0.02	0.07	0.12	0.24	0.46	0.80	1.22	1.52	2.21
Ma	0.15	0.32	0.45	0.76	1.25	1.92	2.68	3.22	4.41
Ap	0.22	0.49	0.71	1.24	2.09	3.27	4.65	5.63	7.78
Ma	0.39	0.76	1.05	1.71	2.72	4.07	5.61	6.69	9.04
Jn	0.98	1.57	1.97	2.80	3.97	5.42	7.00	8.07	10.35
Ju	0.77	1.28	1.63	2.37	3.43	4.76	6.22	7.22	9.34
Au	0.32	0.70	1.00	1.71	2.83	4.38	6.18	7.45	10.23
Se	0.22	0.50	0.73	1.26	2.13	3.33	4.73	5.72	7.91
Oc	0.06	0.17	0.31	0.70	1.48	2.70	4.25	5.41	8.13
No	0.11	0.25	0.36	0.63	1.08	1.69	2.42	2.93	4.06
De	0.07	0.16	0.24	0.41	0.69	1.08	1.53	1.85	2.56
Period									
An	15.87	18.47	19.97	22.65	25.92	29.48	32.94	35.14	39.52
Wi	0.71	1.02	1.21	1.60	2.13	2.76	3.43	3.87	4.79
Sp	2.35	3.30	3.91	5.09	6.66	8.53	10.48	11.77	14.46
Su	5.17	6.57	7.42	9.00	11.00	13.28	15.58	17.08	20.12
Fa	1.51	2.30	2.82	3.88	5.35	7.15	9.07	10.36	13.09

Table E.3.22 Monthly probability distributions for precipitation at Park Rapids, MN (1948-1994) Probability (pct) and Precipitation (in)

MO	1%	5%	10%	25%	50%	75%	90%	95%	99%
Ja	0.04	0.10	0.16	0.32	0.60	1.01	1.51	1.87	2.68
Fe	0.02	0.05	0.09	0.19	0.38	0.68	1.05	1.32	1.93
Ma	0.16	0.31	0.42	0.66	1.03	1.51	2.06	2.44	3.26
Ap	0.24	0.50	0.71	1.19	1.94	2.96	4.14	4.97	6.78
Ma	0.38	0.74	1.02	1.64	2.61	3.89	5.36	6.38	8.60
Jn	0.79	1.36	1.76	2.62	3.86	5.46	7.22	8.42	11.01
Ju	0.39	0.84	1.21	2.07	3.44	5.34	7.53	9.09	12.50
Au	0.38	0.82	1.17	1.99	3.30	5.09	7.17	8.63	11.84
Se	0.27	0.58	0.82	1.39	2.29	3.53	4.95	5.96	8.17
Oc	0.08	0.24	0.40	0.83	1.62	2.82	4.28	5.35	7.78
No	0.12	0.25	0.34	0.56	0.90	1.37	1.89	2.26	3.07
De	0.08	0.17	0.24	0.41	0.69	1.07	1.51	1.82	2.49
Period									
An	15.50	18.13	19.66	22.40	25.74	29.39	32.96	35.22	39.73
Wi	0.60	0.88	1.06	1.41	1.89	2.46	3.07	3.47	4.32
Sp	2.21	3.06	3.60	4.64	6.02	7.66	9.35	10.48	12.81
Su	4.93	6.50	7.47	9.31	11.68	14.43	17.24	19.08	22.86
Fa	1.58	2.37	2.89	3.93	5.36	7.10	8.96	10.20	12.82

Table E.3.23 Monthly probability distributions for precipitation at Long Prairie, MN (1948-1994) Probability (pct) and Precipitation (in)

MO	1%	5%	10%	25%	50%	75%	90%	95%	99%
Ja	0.03	0.09	0.16	0.36	0.75	1.38	2.17	2.75	4.14
Fe	0.00	0.06	0.13	0.30	0.60	1.05	1.60	1.99	2.90
Ma	0.11	0.28	0.43	0.79	1.40	2.27	3.30	4.04	5.69
Ap	0.00	0.40	0.66	1.21	2.05	3.19	4.51	5.43	7.47
Ma	0.53	0.94	1.23	1.87	2.81	4.03	5.39	6.32	8.33
Jn	0.77	1.32	1.70	2.52	3.72	5.24	6.92	8.08	10.55
Ju	0.49	0.96	1.31	2.10	3.30	4.91	6.72	7.99	10.75
Au	0.45	0.88	1.21	1.96	3.11	4.64	6.39	7.60	10.26
Se	0.29	0.60	0.84	1.40	2.29	3.49	4.87	5.84	7.97
Oc	0.07	0.21	0.36	0.79	1.58	2.80	4.31	5.43	7.97
No	0.07	0.19	0.30	0.58	1.09	1.83	2.72	3.37	4.82
De	0.09	0.19	0.27	0.47	0.79	1.22	1.73	2.09	2.88
Period									
An	15.25	18.28	20.05	23.26	27.23	31.62	35.95	38.71	44.26
Wi	0.75	1.13	1.37	1.87	2.54	3.37	4.24	4.83	6.07
Sp	2.90	3.85	4.44	5.55	6.99	8.66	10.37	11.49	13.80
Su	4.48	5.98	6.91	8.68	10.98	13.66	16.40	18.20	21.91
Fa	1.27	2.10	2.67	3.86	5.57	7.73	10.08	11.68	15.11

Table E.3.24 Monthly probability distributions for precipitation at Little Falls, MN (1948-1994) Probability (pct) and Precipitation (in)

MO	1%	5%	10%	25%	50%	75%	90%	95%	99%
Ja	0.00	0.05	0.11	0.26	0.53	0.94	1.45	1.82	2.66
Fe	0.00	0.00	0.01	0.14	0.38	0.80	1.36	1.81	3.67
Ma	0.12	0.27	0.39	0.67	1.13	1.78	2.52	3.05	4.22
Ap	0.00	0.36	0.59	1.09	1.84	2.87	4.05	4.88	6.71
Ma	0.63	1.04	1.33	1.92	2.78	3.86	5.04	5.85	7.57
Jn	0.95	1.54	1.94	2.78	3.97	5.47	7.09	8.19	10.54
Ju	0.79	1.30	1.65	2.39	3.45	4.79	6.24	7.24	9.36
Au	0.49	0.96	1.31	2.11	3.34	4.98	6.85	8.15	10.98
Se	0.34	0.66	0.90	1.44	2.26	3.36	4.61	5.48	7.37
Oc	0.05	0.17	0.31	0.73	1.57	2.91	4.63	5.92	9.08
No	0.05	0.15	0.25	0.50	0.96	1.64	2.47	3.07	4.43
De	0.00	0.07	0.13	0.28	0.55	0.94	1.41	1.74	2.50
Period									
An	15.48	18.15	19.69	22.46	25.83	29.52	33.13	35.43	40.00
Wi	0.38	0.64	0.82	1.20	1.74	2.43	3.19	3.70	4.81
Sp	2.29	3.16	3.70	4.76	6.17	7.82	9.54	10.67	13.02
Su	5.36	6.83	7.73	9.39	11.52	13.94	16.38	17.97	21.21
Fa	1.22	2.02	2.58	3.74	5.41	7.52	9.83	11.40	14.76

Table E.3.25 Monthly probability distributions for precipitation at Collegeville, MN (1948-1994) Probability (pct) and Precipitation (in)

MO	1%	5%	10%	25%	50%	75%	90%	95%	99%
Ja	0.04	0.11	0.18	0.37	0.71	1.21	1.82	2.26	3.27
Fe	0.02	0.06	0.11	0.26	0.55	1.02	1.62	2.07	3.17
Ma	0.19	0.39	0.54	0.88	1.40	2.10	2.91	3.47	4.69
Ap	0.16	0.39	0.60	1.10	1.94	3.15	4.58	5.61	7.89
Ma	0.66	1.13	1.46	2.16	3.17	4.47	5.89	6.87	8.96
Jn	0.62	1.19	1.62	2.59	4.06	6.02	8.23	9.78	13.13
Ju	0.59	1.02	1.33	1.99	2.97	4.21	5.59	6.54	8.58
Au	0.73	1.26	1.64	2.45	3.63	5.15	6.82	7.98	10.44
Se	0.40	0.79	1.09	1.76	2.79	4.16	5.73	6.82	9.19
Oc	0.08	0.24	0.40	0.85	1.69	2.98	4.57	5.73	8.39
No	0.06	0.18	0.29	0.59	1.13	1.93	2.91	3.62	5.23
De	0.04	0.11	0.18	0.35	0.66	1.11	1.66	2.05	2.94
Period									
An	15.27	18.44	20.31	23.72	27.93	32.62	37.26	40.23	46.21
Wi	0.54	0.88	1.11	1.58	2.26	3.10	4.02	4.65	5.97
Sp	2.29	3.31	3.97	5.27	7.02	9.12	11.34	12.81	15.90
Su	4.73	6.28	7.24	9.06	11.43	14.18	16.99	18.84	22.63
Fa	1.66	2.60	3.22	4.50	6.29	8.49	10.87	12.48	15.88

Table E.3.26 April through October frequency distributions of 24 hr rainfall events greater than or equal to 0.5, 1.0, 2.0, and 3.0 inches at six climate stations in north-central Minnesota (1948-1994). Number of events.

Location	APR	MAY	JUN	JUL	AUG	SEP	OCT
PRECIPITATION>0.5 INCHES							
St Cloud	75	93	139	116	124	93	53
Wadena	76	99	140	112	92	69	55
Park Rapids	62	86	147	108	110	86	56
Long Prairie	69	84	120	106	117	76	57
Little Falls	66	91	130	123	119	79	54
Collegeville	69	106	134	105	126	98	66
PRECIPITATION>1.0 INCHES							
St Cloud	11	25	61	32	59	26	22
Wadena	19	27	56	49	38	20	15
Park Rapids	16	23	44	40	48	26	17
Long Prairie	14	29	46	47	43	28	20
Little Falls	17	26	49	47	56	26	25
Collegeville	20	31	55	35	54	31	24
PRECIPITATION>2.0 INCHES							
St Cloud	2	4	17	3	10	5	2
Wadena	1	6	6	8	12	3	4
Park Rapids	2	4	3	11	12	3	4
Long Prairie	1	2	8	9	7	5	4
Little Falls	1	3	11	6	9	1	4
Collegeville	2	4	13	5	10	9	0
PRECIPITATION>3.0 INCHES							
St Cloud	0	2	2	0	5	2	1
Wadena	0	0	1	2	3	2	3
Park Rapids	0	1	2	5	3	0	1
Long Prairie	0	1	1	2	3	0	0
Little Falls	0	0	5	2	3	0	1
Collegeville	0	2	5	0	3	1	0

Daily maximum and minimum temperature probabilities for the six climate stations are listed in Tables E.3.27 through E.3.38. These too were derived from the perod 1948-1994. Most locations show a 25 percent chance of having an 85 degree F or greater maximum temperature during the months of July and August, the peak irrigation season. Temperatures of this magnitude are sufficient to put many crops under stress. For all locations there is a 10 percent probability of reaching maximum temperatures in the 90s during the mid to late summer. Thus one year in ten, irrigation systems will likely be stretched to capacity in meeting the water requirement of crops. Based on the design capacities and cycling times of most center pivot systems, irrigation would need to occur almost continously to get through such periods of temperature without severe crop stress.

Summary: Probability distributions of precipitation, as well as maximum and minimum temperature from six climate stations in the north-central region were examined. A high degree of temporal variability is noted at virtually all locations. Heavy rainfall events are found to be much more frequent during the peak summer periods when crop canopies are near maximum and irrigation is most frequent. Occasional heavy rainfalls in the spring and fall months occur at times when there is little if any crop present, yet there may be leachable nitrogen sources in the soil as a result of manure applications or starter fertilizer.

Temperature probabilities show that one year in ten, maximum temperatures are likely to stress the capacity of most irrigation systems to adequately apply water which meets crop needs. Peak irrigation season corresponds to the time of summer with the highest frequency of heavy rainfall events. This increases the risk of leaching nutrients from the soil profile when irrigation occurs just prior to a heavy rainfall event. Greater attention to weather forecasts, particularly the quantified precipitation forecast (QPF) should enable producers to adjust irrigation strategy in order to buffer the soil capacity to handle heavy rainfall.

Table E.3.27 Probability distribution for maximum daily temperature at St Cloud, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-18	-4	0	9	20	29	35	38	56
Fe	-14	3	8	16	26	34	40	44	57
Ma	0	18	22	30	37	43	51	57	79
Ap	20	35	39	45	54	63	71	76	96
Ma	35	50	54	61	69	76	82	86	97
Jn	50	63	67	72	77	83	87	90	102
Ju	58	71	73	78	82	87	91	93	102
Au	55	66	69	74	80	85	89	92	100
Se	41	53	56	62	69	76	82	86	98
Oc	29	40	43	49	57	65	73	76	90
No	-1	19	24	31	38	46	54	58	74
De	-19	2	7	17	26	32	38	41	60
Perod									
An	-19	11	19	33	55	75	83	87	102
Wi	-19	0	5	14	24	32	38	42	60
Sp	0	25	31	40	53	67	76	81	97
Su	50	66	69	74	80	85	89	92	102
Fa	-1	27	32	43	56	68	76	81	98

Table E.3.28 Probability distribution for maximum daily temperature at Wadena, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-23	-7	-2	6	18	27	33	37	55
Fe	-20	1	5	14	25	33	38	42	60
Ma	-4	15	20	28	35	42	48	53	75
Ap	16	34	38	43	52	62	70	75	96
Ma	35	48	53	60	68	75	81	84	96
Jn	52	61	64	70	75	81	86	89	97
Ju	56	68	71	76	80	85	89	92	101
Au	57	65	68	73	79	84	88	91	102
Se	39	51	54	61	68	75	81	85	96
Oc	25	38	41	48	56	64	71	75	94
No	-2	17	22	29	36	45	53	58	74
De	-19	0	5	14	24	32	37	40	60
Period									
An	-23	8	17	32	54	73	82	86	102
Wi	-23	-3	2	11	22	31	36	40	60
Sp	-4	23	30	38	51	65	75	79	96
Su	52	64	67	73	78	83	88	91	102
Fa	-2	25	31	41	55	66	75	80	96

Table E.3.29 Probability distribution for maximum daily temperature at Park Rapids, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-22	-6	-2	7	18	26	33	36	51
Fe	-20	2	7	15	25	34	40	43	61
Ma	0	16	22	29	36	43	50	54	74
Ap	12	35	38	44	53	62	70	75	96
Ma	33	48	53	61	68	75	81	84	96
Jn	47	63	66	71	76	82	86	89	96
Ju	56	70	72	76	81	85	90	91	100
Au	55	66	69	74	79	84	89	91	101
Se	37	52	55	61	68	75	81	84	99
Oc	26	37	41	48	56	65	71	75	90
No	-3	17	22	28	35	44	52	56	72
De	-19	1	5	14	23	30	36	40	58
Period									
An	-22	9	17	31	54	74	82	86	101
Wi	-22	-2	3	11	22	30	36	40	61
Sp	0	24	30	39	52	66	75	80	96
Su	47	65	69	74	79	84	89	91	101
Fa	-3	25	30	40	55	67	75	80	99

Table E.3.30 Probability distribution for maximum daily temperature at Long Prairie, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-21	-5	0	9	20	28	35	38	56
Fe	-16	2	8	16	26	35	41	44	59
Ma	-2	17	22	30	37	44	51	57	74
Ap	24	35	38	45	54	64	71	76	95
Ma	33	50	55	62	70	77	82	85	95
Jn	50	64	67	72	78	83	88	90	100
Ju	62	71	74	78	82	87	91	93	103
Au	56	68	70	75	80	85	90	92	102
Se	43	54	57	63	70	77	83	86	95
Oc	27	40	43	51	58	66	73	76	90
No	1	18	24	30	38	46	55	58	73
De	-18	1	6	16	26	32	38	41	59
Period									
An	-21	10	19	33	56	75	83	87	103
Wi	-21	-1	4	13	24	32	38	42	59
Sp	-2	25	31	40	54	67	76	81	95
Su	50	67	70	75	80	85	90	92	103
Fa	1	27	32	43	57	69	77	81	95

Table E.3.31 Probability distribution for maximum daily temperature at Little Falls, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-19	-3	1	10	21	29	35	39	54
Fe	-10	4	10	18	27	35	41	44	58
Ma	-4	20	24	32	38	45	52	57	75
Ap	24	37	40	47	56	65	72	77	95
Ma	35	52	57	64	71	78	83	86	95
Jn	50	66	69	74	79	84	88	91	99
Ju	60	73	75	79	83	88	91	93	102
Au	56	69	71	76	81	86	90	92	101
Se	43	55	59	64	71	78	83	87	99
Oc	28	41	45	51	59	67	73	77	91
No	0	19	26	32	39	47	55	59	75
De	-15	4	8	17	26	33	38	41	60
<u>Period</u>									
An	-19	12	20	34	57	76	84	88	102
Wi	-19	0	5	15	25	33	38	42	60
Sp	-4	27	33	41	55	69	78	82	95
Su	50	69	72	76	81	86	90	92	102
Fa	0	28	33	44	58	70	77	81	99

Table E.3.32 Probability distribution for maximum daily temperature at Collegeville, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-23	-4	0	9	21	29	36	39	54
Fe	-16	3	8	17	27	35	41	45	60
Ma	1	18	22	30	37	44	51	57	77
Ap	23	36	39	46	55	63	72	76	95
Ma	35	52	55	63	70	76	82	85	96
Jn	50	65	68	72	78	83	87	90	101
Ju	59	72	74	78	82	86	90	92	103
Au	56	68	70	75	80	85	89	91	100
Se	42	54	57	63	70	76	82	86	97
Oc	29	40	44	51	58	66	73	76	89
No	2	18	24	31	38	47	54	58	74
De	-20	3	8	17	26	33	39	41	58
<u>Period</u>									
An	-23	11	20	33	56	75	83	87	103
Wi	-23	0	5	14	24	33	38	42	60
Sp	1	26	31	40	54	67	76	81	96
Su	50	67	71	75	80	85	89	91	103
Fa	2	27	33	43	57	68	76	81	97

Table E.3.33 Probability distribution for minimum daily temperature at St Cloud, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-43	-26	-22	-13	-2	9	18	22	32
Fe	-35	-21	-16	-8	4	15	24	28	36
Ma	-32	-8	-2	9	19	27	32	35	50
Ap	-3	18	21	26	32	38	44	47	61
Ma	19	30	33	38	43	50	56	59	69
Jn	32	40	43	48	54	58	63	65	77
Ju	40	47	50	54	58	63	66	69	77
Au	33	44	46	51	56	61	65	67	78
Se	18	31	34	40	46	52	58	61	73
Oc	5	20	24	29	35	42	47	51	65
No	-20	-1	5	14	22	29	33	37	50
De	-41	-18	-13	-4	6	17	24	27	42
<u>Period</u>									
An	-43	-12	-3	15	33	50	59	63	78
Wi	-43	-22	-18	-9	3	14	22	27	42
Sp	-32	2	11	23	32	41	50	54	69
Su	32	43	46	51	56	61	65	67	78
Fa	-20	9	16	25	34	44	52	56	73

Table E.3.34 Probability distribution for minimum daily temperature at Wadena, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-41	-29	-25	-17	-5	7	16	20	31
Fe	-39	-24	-20	-12	1	13	21	26	34
Ma	-33	-12	-6	5	17	25	30	33	48
Ap	-7	15	19	25	30	35	41	45	57
Ma	18	29	31	36	42	49	55	58	70
Jn	33	40	43	48	53	57	62	64	73
Ju	37	47	49	53	57	62	65	67	78
Au	36	43	46	50	55	60	64	66	77
Se	17	31	34	39	45	51	56	60	72
Oc	2	20	23	28	34	40	45	50	64
No	-22	-3	3	12	21	27	32	35	52
De	-42	-20	-16	-8	4	15	22	25	42
<u>Period</u>									
An	-42	-15	-7	13	32	49	58	62	78
Wi	-42	-26	-21	-12	0	12	20	24	42
Sp	-33	-2	7	21	30	40	48	53	70
Su	33	43	46	50	55	60	64	66	78
Fa	-22	7	14	24	33	43	50	55	72

Table E.3.35 Probability distribution for minimum daily temperature at Park Rapids, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-45	-32	-28	-18	-8	6	14	19	31
Fe	-42	-28	-23	-13	0	13	21	25	36
Ma	-36	-15	-9	3	16	24	30	33	49
Ap	-8	13	18	23	29	35	41	45	62
Ma	14	26	30	35	41	48	54	57	70
Jn	28	38	41	46	52	57	61	63	73
Ju	35	45	47	52	56	61	65	67	78
Au	31	42	44	49	55	60	63	65	75
Se	17	30	33	38	44	51	56	60	70
Oc	-2	19	22	27	33	40	45	49	68
No	-29	-6	1	11	21	26	32	35	52
De	-46	-24	-19	-10	3	14	21	24	40
Period									
An	-46	-18	-9	12	31	49	57	61	78
Wi	-46	-29	-24	-14	-1	11	20	23	40
Sp	-36	-5	5	20	30	39	47	52	70
Su	28	41	44	49	54	60	63	65	78
Fa	-29	5	13	23	32	42	50	54	70

Table E.3.36 Probability distribution for minimum daily temperature at Long Prairie, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-40	-28	-23	-14	-3	10	18	22	33
Fe	-42	-24	-19	-10	3	15	25	28	37
Ma	-35	-11	-4	7	19	27	32	35	50
Ap	-7	17	20	26	31	38	44	48	61
Ma	19	29	32	37	44	51	57	59	71
Jn	30	40	43	48	54	59	63	66	76
Ju	35	46	49	53	58	63	67	69	80
Au	33	43	45	50	56	61	65	68	80
Se	19	31	34	40	46	52	58	62	74
Oc	3	20	24	29	35	42	48	52	65
No	-23	-1	5	14	23	29	33	38	55
De	-39	-19	-14	-5	6	17	23	27	44
Period									
An	-42	-13	-5	15	33	50	59	63	80
Wi	-42	-24	-20	-10	2	14	23	27	44
Sp	-35	-1	9	22	31	41	50	55	71
Su	30	42	45	51	56	61	65	68	80
Fa	-23	9	15	25	34	44	52	57	74

Table E.3.37 Probability distribution for minimum daily temperature at Little Falls, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-41	-27	-23	-14	-3	10	18	22	34
Fe	-37	-23	-18	-9	4	16	24	27	35
Ma	-39	-9	-4	8	19	26	32	34	48
Ap	-5	16	20	26	31	37	44	47	63
Ma	18	29	32	37	44	51	56	59	70
Jn	34	41	43	49	54	59	63	65	74
Ju	39	48	50	54	59	63	67	69	79
Au	36	44	47	51	56	61	65	68	77
Se	17	32	35	40	47	53	58	62	72
Oc	5	21	24	30	36	42	48	51	65
No	-24	-1	7	15	23	29	34	38	53
De	-42	-19	-13	-5	7	17	24	27	43
Period									
An	-42	-12	-4	15	34	51	59	63	79
Wi	-42	-24	-20	-10	3	14	22	26	43
Sp	-39	0	10	22	32	41	50	55	70
Su	34	43	46	51	56	61	65	68	79
Fa	-24	10	17	26	35	45	52	57	72

Table E.3.38 Probability distribution for minimum daily temperature at Collegeville, MN (1948-1994)

MO	Low	5%	10%	25%	50%	75%	90%	95%	High
Ja	-36	-22	-19	-11	0	12	20	24	35
Fe	-30	-18	-14	-5	7	18	26	30	50
Ma	-30	-5	0	10	21	28	33	36	50
Ap	2	19	23	28	33	40	46	50	63
Ma	19	32	35	40	46	53	59	61	69
Jn	35	43	46	51	56	61	65	67	77
Ju	41	51	53	57	61	65	68	70	79
Au	39	48	50	54	59	64	67	69	77
Se	23	36	39	44	49	55	60	65	75
Oc	13	25	28	32	38	45	50	53	65
No	-19	2	9	17	25	31	36	40	56
De	-35	-15	-10	-2	9	20	26	29	43
Period									
An	-36	-9	-1	18	36	53	62	65	79
Wi	-36	-19	-15	-6	6	17	24	28	50
Sp	-30	5	12	24	34	44	53	57	69
Su	35	47	50	54	59	63	67	70	79
Fa	-19	12	19	28	38	47	55	59	75

E.3.4 Applications of climatic data to spray occasions

Introduction: The irrigated soils of north-central Minnesota not only require careful management of water and plant nutrients, but great care must be used in the application of herbicides in order to limit leaching of material to ground acquifers, loss by runoff, or injury to nearby sensitive crops due to vapor drift.

Mechanical, cultural and chemical forms of weed control are used. The use of postemergence herbicides has been increasing in recent years, as producers have sought more flexibility in controlling weeds with a combination of methods. Late spring or early summer weed flushes missed by soil applied herbicides, cultivations or rotary hoes are often treated with specific postemergence compounds.

Spackman (1983) and others have developed techniques to estimate the suitability of spraying occasions for various types of herbicides. Postemergence herbicides as a class of compounds often show the greatest sensitivity to meteorological conditions. Very few if any are totally weather proof. Several environmental parameters just before, during and after application of a postemergence herbicide can greatly govern its efficacy, residence time on the foliage or soil surface, and volatilization.

Spackman's criteria for postemergence herbicides are the following conditions:

Daylight hours for aircraft or ground spraying
Air temperature between 50 and 85 degrees F
No precipitation within 12 hours of application
Relative humidity between 40 and 95 percent
Wind speed less than 10 mph (5 mph with especially volatile compounds)

Some of these criteria are specifically referenced on product labels, while others are more generic to a class of herbicides with similar modes of action. These conditions must be satisfied for a period of five hours to allow for the necessary logistics to apply a herbicide by ground or air to a significant amount of crop acreage.

Results: These criteria were used to screen the hourly climatic data from the Staples Irrigation Center during the 1994 crop season. The period corresonding to application of postemergence herbicides, May 23 to June 24 was examined in order to identify the number of spraying-occasions which satisfied all criteria simultaneously. In addition, successively dropping individual criteria was used as a technique to evaluate which were the most restrictive with respect to the use of postemergence compounds in the north-central region.

Figure E.3.3 shows the daily frequency of spraying occasions at Staples, MN during May 23 to June 24, 1994. Wind speed was by far the most restrictive climatic element in limiting spraying-occasions. The two wind criteria used for selecting spraying occasions were speeds less than 10 mph and speeds less than 5 mph, both of which are commonly recommended by agronomists or cited on label instructions. The number of spraying occasions which met the 10 mph wind speed criteria (122 cases) were six times more than the number which met the 5 mph criteria (21 cases). This suggests opportunities to use any compounds which impose a risk associated with spray droplet or vapor drift are far fewer than for those which pose no such risk.

Spraying occasions were far more numerous in the early morning hours than any other time of day. It was unusual to find a period of three or more consecutive days without a spraying occasion. However, this may be an attribute characteristic of the 1994 crop season that is somewhat rare. Subsequent research in this area could be directed to screening for spraying-occasions for other classes of herbicides at other locations in the landscape and for examining a series of years to see what the temporal variability in spraying occasions for specific compounds is.

Summary: Using detailed hourly data, environmental variables can be screened to identify spraying occasions for specific kinds of herbicides. Generally, label instructions or agronomic recommendations supply the necessary environmental thresholds concerning efficacy, carryover, and drift potential of these compounds. Opportunities to properly use herbicides vary a great deal over time and space. The use of hourly climatic data to identify spraying occasions on an annual basis may provide a 'climatology' useful for the selection of herbicides based on more site specific environmental criteria than presently used.

References:

Baker, D.G., Nelson, W.W., and E.L. Kuehnast. 1979. Climate of Minnesota: Part XII The Hydrologic Cycle and Soil Water. Univ. of MN Agric. Exp. Sta. Tech. Bul. 322, 23pp.

Jones, C.A. and J.R. Kiniry. 1986. CERES-Maize, A Simulation Model of Maize Growth and Development. Pub. Texas A&M Univ. Press.

Kuehnast, E.L., Baker, D.G. and J.A. Zandlo. 1982. Climate of Minnesota: Part XIII Duration and Depth of Snow Cover. Univ. of MN Agric. Exp. Sta. Tech. Bul. 333, 24pp.

Malzer, G.L., Seeley, M.W., and J.L. Anderson. 1983. Nitrogen Loss Potential and Nitrogen Fertilizer Management of Minnesota Soils. Univ. of MN Agric. Exp. Sta. Rep. 186, 4pp.

Spackman, E.A. 1983. Weather and the variation in numbers of spraying-occasions. Aspects of App. Biology 4:317-327.

Thompson, N. 1983. Meteorology and crop spraying. Meteorology Magazine 112:249-259. Royal Meteorological Society.

Figure E.3.1

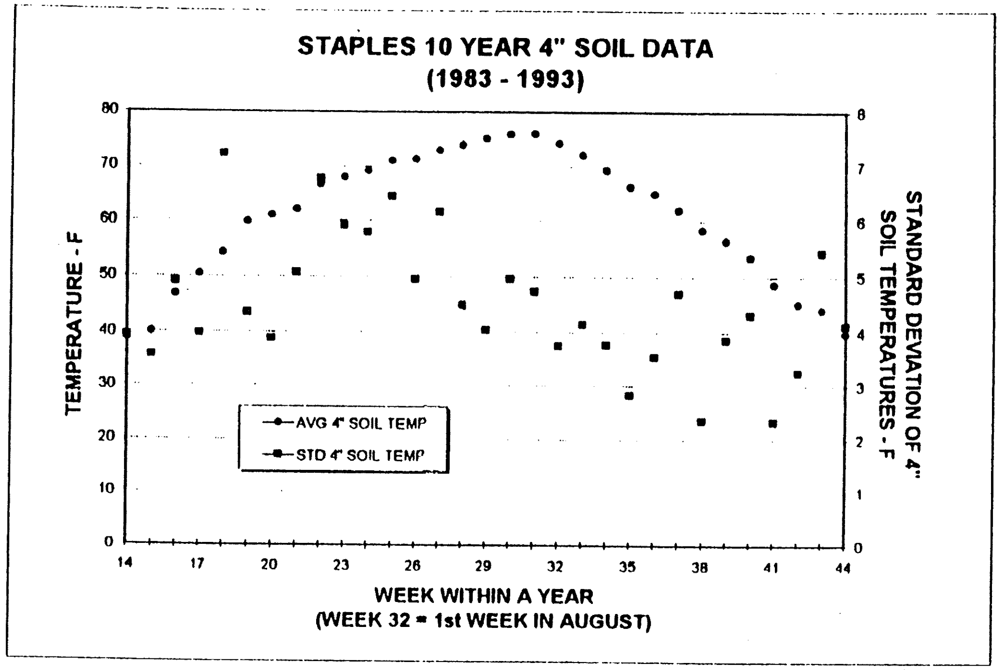


Figure E.3.2

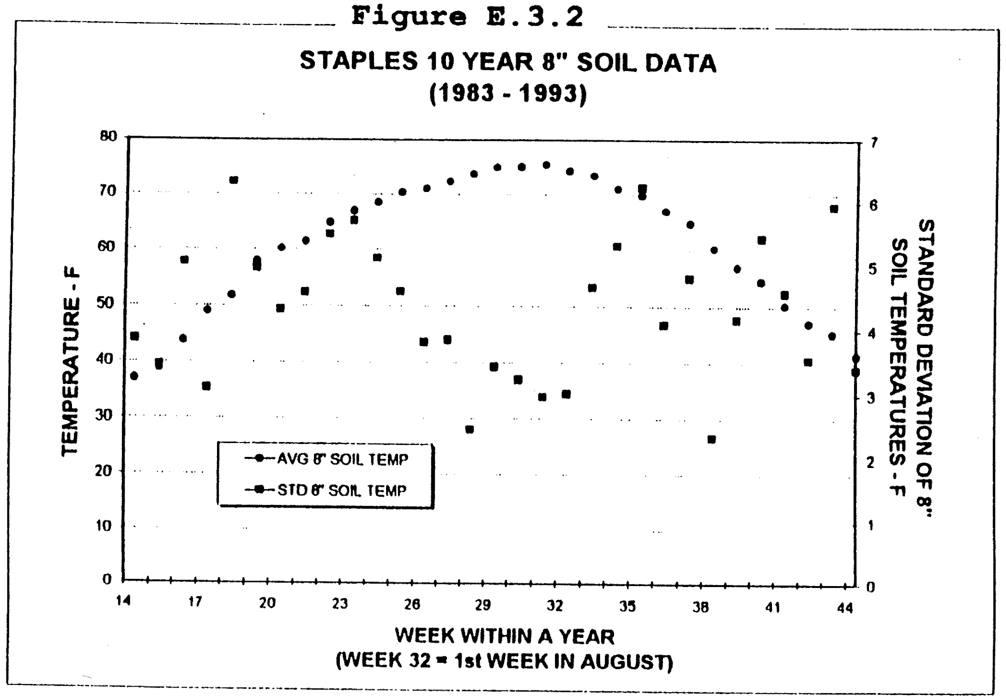
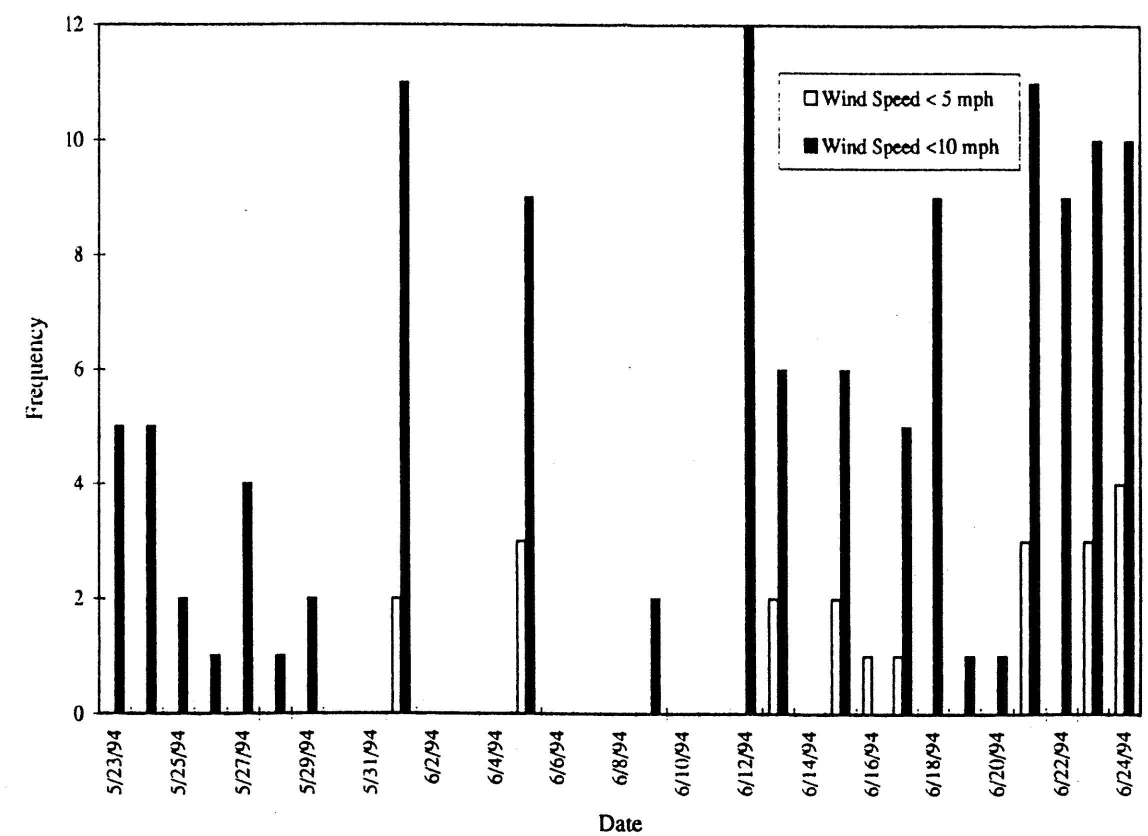


Figure E.3.3

Number of Spray Occassions by Date at Staples, MN (1994)



Simulation Modelling of Nitrate Leaching from Potato Production on the Anoka Sand Plains.

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Summary

Farming on sandy soils has a history of problems with nitrate leaching. Optimizing nitrogen use can reduce groundwater nitrate levels, and enhance crop development at the same time. This is the final report on simulation modelling activities for potato farming on the Anoka Sand Plains. The study's goal was to use NCSWAP as a real-time crop nitrogen management tool, helping growers better understand the implications of their nitrogen management practices. Examined simultaneously, were the model's predictive accuracy and the information value of the output. Written materials from the two-year study period are assembled in this report. Activities began in April of the 1993 crop season, and were completed in June 1995.

Part 1. covers the most recent analysis, the 1994 crop season. This section explains the factors and assumptions that go into NCSWAP's calculations, and compares the simulations to field data. Recommendations from this section include, better irrigation management practices and more accurate nitrogen crediting.

Part 2. examines the models performance after the 1993 crop season. This first cropping period was used to validate the model, and develop appropriate information summaries. The sensitivity analysis recommended a number of changes to the model, which were incorporated into the 1994 field condition estimates.

Part 3. is a series of field conditions reports issued at important points in the crop nitrogen development cycle; preplant, emergence, hilling, and harvest. Each simulation covers soil moisture, plant growth and nitrogen uptake, and soil nitrate levels. Climate information is included for reference. Advisories were communicated to the grower directly.

Part 1.

Activity: Summarize the model's nitrogen mass balance estimations for the 1994 growing season. Explain important NCSWAP modelling assumptions, and compare the 1994 model predictions to field data. Run alternative irrigation and nitrogen crediting scenarios, and suggest practice changes.

Outcome: NCSWAP made a number of insightful predictions during the 1994 season. Performance was significantly improved over 1993. Nitrogen management recommendations include lowering irrigation levels, and raising credits counted for other nitrogen sources.

Period: October 1994 through June 1995

By J.A.E. Molina and Barry Ryan January 4, 1994

INTRODUCTION

This report contains the simulation modelling estimates of the impacts from nitrogen management practices at the Becker K&O Sap test-site during the 1994 crop season. The research objective was to assist the grower better manage his nitrogen resources by supplying him with real-time computer analysis of field nitrogen conditions. Of particular concern was the potential for nitrate leaching past the plant root zone. The nitrogen mass balance, an accounting of all nitrogen sources in the system from the start of the growing season to the end, is the primary focus of this report. Modelling a complex agricultural system requires the acceptance of a great number of simplifications and best-guess assumptions. A brief and partial description of some important model assumptions are outlined in the first section of this report. The second section details the results of the 1994 season in terms of the nitrogen mass balance. In summary, as much as 47-percent of the grower supplied nitrogen leached past the plant root zone and was lost to the water table. The model also detected a period of nitrogen stress during the growing season, which ultimately resulted in an estimated yield loss of about 2-percent. Finally, section 3 examines how the nitrogen mass balance would change if the grower's irrigation schedule were reduced by half, and credits were taken for nitrates in the irrigation water.

SECTION 1 > Details of the Modelling Assumptions.

The Simulation Model

Estimates of the nitrogen mass balance were made using a computer simulation program called NCSWAP. This model combines climate data with crop management decisions to study their impact on the soil, water, and plant systems. Nitrogen levels in these various components may rise or fall over the growing season, based largely on the assumptions made about their individual characteristics. Hence, it is important for an understanding of the model's findings that a number of these significant assumptions first be examined. The rest of this section, therefore, describes the soil profile and its hydraulic characteristics, assumptions about chemical and biological transformations, and factors affecting crop development. The simulation period starts on April 11th --the day before planting-- and ends with harvest on September 11th (153 days).

The Soil Profile:

The Becker site is located on the Anoka sand plain, and consists primarily of a loam-sandy soil, generically known as a Hubbard. Field samples were taken to define horizons within the soil profile which share homogeneous soil properties. For this simulation the profile geometry includes 5 horizons (table 1). These horizons are arranged in a series of depths from the surface to 120 cm (or about 4 feet). Each horizon is further divided into 6 cm. segments, for a total of 20 segments. While the choices of horizon depths are somewhat arbitrary, they also reflect other real considerations. The third horizon for instance is something of a "plowpan",representing conditions of repeated compaction; mechanical and other. The 120 cm. profile bottom is nearly equivalent to the depth of the suction tubes used to measure soil water nitrate concentrations in a related field experiment.

Table 1 ----- Initial Physical Properties by Soil Horizon -----

HORIZON #	DEPTH (cm.)	TEXTURE	BULK DENSITY (gm/cm3)
1	0-6	Loam Sand	1.54
2	6-36	Loam Sand	1.60
3	36-48	Loam Sand	1.62
4	48-72	Loam Sand	1.65
5	72-120	Sand	1.66

Each horizon is assigned a value for the soils bulk density. This number is a measure of the mass or weight of a unit volume of dry soil; including both solids and pores. Bulk density increases in value with depth -- as an expression of compactness. Despite the profile's relatively high bulk density, and the existence of the plowpan layer, the sandy nature of the Becker soil makes for moderately- to excessively-well drained soil conditions.

The surface horizon, in particular the top segment, plays an important part in the simulation process. For simplicity, the surface is assumed to be 100 percent bare. No reduction in evaporation occurs due to residue, and only the first segment (top 6cm) contributes to evaporation. Tillage events are considered by the model, and they have an impact on the bulk densities of the segments affected. The bulk density of the top segment is also affected by the impact of rain and irrigation events. Over time, however, the soil segments return to the bulk density table values.

The Hydraulic Profile:

A second set of assumptions must be assigned for the hydraulic properties of each horizon (Table 2). The initial gravimetric water content of the profile is set to a near field capacity condition, as determined by field observation. The field soil water content at water stress, saturation and field capacity, are further described both in terms of gravimetric and volumetric measures. These two measures relate similar information about the profile water content. Gravimetric measures indicate the amount of water per gram of soil or mass, while volumetric measures represent the amount of water per volume of soil. Both are related to bulk density, and reflect the inter-related nature of water movement through the soil profile.

Table 2 Initial Hydraulic Properties Per Horizon -- Water Content

Horizon	Initial Content (ml/gm)	@ Water Stress Gravimetric (ml/gm)	Volume (ml/cm3)	@ Saturation Gravimetric (ml/gm)	@ Water Fld Cap. Volume (ml/cm3)	Gravimetric (ml/gm)	Volume % (ml/cm3)	Saturation
1	0.139	0.037	0.057	0.270	0.416	0.149	0.229	55.00
2	0.128	0.036	0.058	0.250	0.400	0.138	0.220	55.00
3	0.122	0.030	0.049	0.240	0.389	0.132	0.214	55.00
4	0.117	0.020	0.033	0.230	0.380	0.127	0.209	55.00
5	0.111	0.100	0.166	0.220	0.365	0.121	0.201	55.00

Rain and irrigation add moisture to the hydraulic profile dynamics over the growing season. NCSWAP equilibrates soil water back to field capacity in 2 days for light soils like the Becker Hubbard, and in 3-5 days for heavier soils. The redistributive flow is only in a downward direction; no upward capillary suction is assumed to occur. With the exception of the third horizon "plowpan", saturated hydraulic conductivity is high and does not limit flow. While the model is capable of impeding water movement through the lower boundary of the profile, the lower bound in this analysis is open to drainage.

NCSWAP is sensitive to plant stress from inadequate moisture, and crop development begins to suffer when segments in the root zone fall below their water stress levels. The model does not, however, impede plant development when profile water content values exceed the water saturation limits. When rain or irrigation events occur, the computational time-step for soil biological transformations and infiltration processes is 5 times a day; otherwise it is once a day. Root and crop top growth are always computed once a day. During the 1994 season, steady rains and ample irrigation held field soil water conditions at or near field capacity -- according to both field observation and model estimate.

Chemical and Biological Transformations:

The next set of assumptions create the framework for the chemical and biological processes that drive seasonal changes in the active organic pool of nitrogen (table 3). This pool is an important "natural" source of plant nitrogen, and includes the microbial mass (Pool I) and nutrient humus (Pool II). Activity within the microbial mass is affected by factors such as, the amount of residue, water content, temperature, and the availability of nitrogen in the soil profile. Pool I activity supplies or depletes the level of plant available nitrogen stored in the nutrient humus of pool II. If over time the humus nitrogen degradation is greater than the nutrient replenishment, the soil fertility will go down. Conversely, this humus degradation also represents nourishment for the growing crop.

Table 3 assigns a carbon content and C:N ratio to each horizon. The initial size of the active organic pool in the total 120 cm. profile was estimated at 215 kg/ha, while the initial level of inorganic nitrogen in the profile was set at 30 kg/ha. The stable humus (Pool III), much as the name suggests is stable, and was held constant throughout this analysis. Notice that only the first two horizons of the profile had measurable levels of nutrient materials.

Table 3 ------ Initial Chemical and Biochemical Properties per Horizon ------

HORIZON	TOTAL PPM N	NH4 PPM N	NO3 PPM N	POOL 0+I + NIT UREA PPM C	(MICROBIALMASS) C/N	POOL II PPM C	(NUTRIENTHUMUS) C/N	POOL III PPM C	(STABLEHUMUS) C/N
1	0.7	1.9	0.0	70.0	10.0	1000.0	20.0	0.0	20.0
2	0.7	1.9	0.0	30.0	10.0	500.0	20.0	0.0	20.0
3	0.4	1.4	0.0	0.0	10.0	0.0	20.0	0.0	20.0
4	0.5	1.1	0.0	0.0	10.0	0.0	20.0	0.0	20.0
5	0.2	0.5	0.0	0.0	10.0	0.0	20.0	0.0	20.0

Several other nitrogen related factors are worth noting briefly as well. Nitrification rates govern the transformation of ammonium to nitrates, and differ in the first 2 horizons from the rest of the profile. From the surface to 36 cm. the nitrification rate is 15 ppm/day, while below that level it falls to 5 ppm/day. The ratio of soluble to total NH4 was set at 0.2 for the first 2 horizons, and at 0.5 for the remaining 3 horizons. The process transforming ammonium to nitrate (nitrification) is affected by soil temperature and soil water content levels; specifically where saturation conditions occur. At near-saturation levels, nitrification is replaced by denitrification. Denitrification is the process by which nitrogen (nitrate) is biologically converted to gaseous nitrogen, which is subject to atmospheric losses. Finally, the downward flow of soluble (inorganic) nitrogen is set at 65-percent that of the water flow.

Reference Crop Details.

An important feature of NCSWAP is the use of a reference crop in defining the simulated crop development. The simulated crop can at best achieve the yield potential of the reference crop, but can not surpass it. The reference crop for this simulation is a potato crop grown in 1991 at the Becker experiment station. No water or nitrogen stress was observed during the 1991 crop development. The effects of air temperature on crop development is computed in terms of degree day accumulation. The model calculates degree days from high and low daily temperature inputs. Plant population was set at 39,500 plants per hectare in keeping with the actions of the grower, and it is assumed that the population remains constant until harvest.

Many other model assumptions are set by the programmer at the start of the season. Of these, the most important crop assumptions are the maximum potential yield and final crop nitrogen content. The maximum potential yield was set at 14,600 kg/ha (dry mass) for total top mass and tuber growth. The final crop nitrogen concentration was assumed to be 1.5 percent. Based on these factors, the maximum potential crop nitrogen uptake was 226 kg/ha. Root mass assumptions are equally important to crop development and nitrogen use. Root penetration occurs at 1 cm./day for the first 36 days, and 0.35 cm./day until 80 days past emergence. Like the above ground crop mass, roots are assumed to be uniformly distributed over the field. Hence, the model can not distinguish between conditions in the furrow and the row.

Rainfall and Irrigation:

Rainfall during the simulation period (April 11 -- Sept. 11) was 60 cm., occurring in 39 events. In addition, the grower added 45 cm. of irrigation water. Nitrate contamination of irrigation wells is a recognized problem on the Anoka sand plain. Typically wells have nitrate concentrations ranging from detectable levels (0.5 ppm) to as high as 40 ppm. Nitrate concentration levels were measured (twice) at 22 ppm from the field site pivot, and this was the level used in simulation. Hence, the irrigator alone is estimated to have contributed 110 kg/ha of nitrogen (nitrate) to the system.

Grower-Supplied Nitrogen Management:

The grower applied nitrogen (N) at a rate of 290 kg/ha over 4 applications. The crop received a starter application of 35 kg/ha on April 12th. Emergence was half complete on May 15. The second (emergence) application was 85 kg/ha on May 21; air delivery, broadcast over the row and cultivated in. The third (hilling) application was 135 kg/ha on May 30; again air delivery, broadcast over the row and cultivated in. As the crop was reaching full development, the fourth and final treatment of 45 kg/ha was applied through the irrigator on July 13th. The crop was killed Sept. 1, and harvested 10 days later. Soil water remained at field capacity all season.

SECTION 2> Simulation Modelling Results -- Nitrogen Mass Balance: Becker Potatoes 1994.

The principle topic of this report is the change in soil-water-plant nitrogen levels over the 1994 growing season for potatoes at Becker. Table 4 summarizes the initial and final values for various components of the nitrogen system. At the center of activity is the crop, which had a total seasonal demand of 220 kg/ha nitrogen. This was only slightly below the reference crop maximum potential N uptake of 226 kg/ha.

On the right side of the table are estimates of initial and final nitrogen conditions in the active organic pool and inorganic profile. The active organic pool fell from 215 kg/ha to 115 kg/ha over the period, while the amount of inorganic N in the profile finished higher, at 45 kg/ha. Combined with the inadvertent addition of 110 kg/ha from the contaminated irrigation well, the total background N contribution totaled 355 kg/ha over the season. The model estimated total crop uptake from these background resources at 95 kg/ha, or 43 percent of the total crop need. Denitrification from background sources was estimated at 20 kg/ha, leaving a 80 kg/ha seasonal leachate total.

Grower-supplied nitrogen totaled 290 kg/ha over the growing season (table left). The crop's remaining N needs (57 percent or 125 kg/ha) were met by the grower-supplied N. Yet, only 43 percent of the grower supplied N was used by the crop. Another 10 percent was lost in small portions to denitrification, root and plant residuals, and the active organic pool. The remaining 47 percent (140 kg/ha) leached past the 120 cm. horizon -- presumably headed for the irrigator wellhead. Add to this amount the 80 kg/ha recycled from background sources, and the total seasonal nitrogen leachate equaled 220 kg/ha. A larger number than most researchers have previously reported.

Paradoxically, the crop experienced nitrogen stress despite the (periodic) over abundance of nitrogen. This clearly demonstrates the opportunity for better management of the rates and timing of nitrogen applications, actions which could both improve yield and reduce nitrate leaching.

Table 4. -- Summary of the nitrogen mass balance. (Kg/Ha)

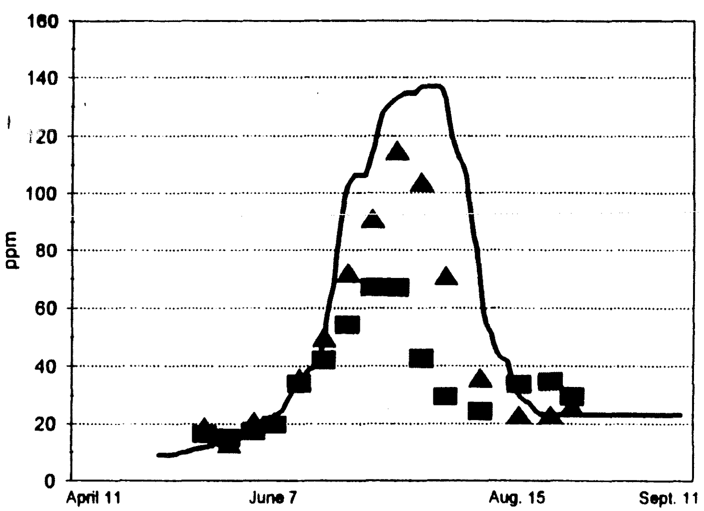
Total System Nitrogen Resources		
Grower-supplied N 290	Background nitrogen sources	355
	- initial active organic	215
	- initial inorganic profile	30
	- seasonal irrigation	110
Total Crop Nitrogen Uptake <220>		
Grower-supplied Crop N <125>	Background Crop N <95>	
Post-harvest Nitrogen Conditions		
Grower-supplied nitrogen	Background N sources	
- residual top mass <0>	- final active organic <115>	
- residual root <15>	- final Inorganic profile <45>	
- denitrification <10>	- denitrification <20>	
Total Nitrogen Leached @ 120 cm.		
Leachate <140>	Leachate <80>	

Model Validation -- Can these numbers be right ?

While point estimates provide valuable information, the nitrogen balance framework outlined above holds the most potential for further analysis. Since the model can simulate individual elements of the nitrogen system separately, and can detail a range of variables, the researcher can manipulate each field assumption and isolate its impact on the overall system. Climate and management decision alternatives may be tested as well. The question to ask yourself in judging the nitrogen balance of table 4, is whether (individually and as a system) the numbers can be deemed "reasonable". Many arguable adjustments could be made to the final N distributions of table 4., but significant total nitrate leaching is difficult to assume away -- even with the most optimistic model adjustments. There are few affordable ways to test the accuracy of agricultural models like NCSWAP. Two independent measures were taken from data collected by colleagues working the same site. First, suction tube water nitrate concentration readings are compared with the model generated estimates. The second validation of model accuracy is based on empirical and anecdotal evidence gathered over the growing season, in particular during a period of crop nitrogen stress.

1. Comparing soil water N concentrations.

One independent check of model accuracy is whether soil-water nitrate concentrations collected in the field can be predicted in simulation. Suction tube data were collected for between-row, within-row, and paratil treatments; four samples were gathered weekly for each treatment. NCSWAP doesn't make such fine distinctions as furrow and row, but it can estimate nitrate concentrations on a daily basis. Graph 1 shows the concentration levels (ppm) of soil water as it leached past the 120 cm. mark. The solid line represents the simulated nitrate concentration levels. The triangular figures mark the measured readings of one individual suction tube -- WB4. Solid square figures mark the average reading for all between-row measurements, including WB4. As self-serving as it may seem, we choose to compare simulated nitrate levels with average between-row readings to demonstrate that model estimates are within the realm of possibility. The average combined between- and within-row values show only a modest elevation in nitrate levels, against the simulated estimates which appear exaggerated. It might even be reasonable to question the overall accuracy of the suction tube readings. One undeniable feature of graph 1 is that sandy soils (at field capacity) quickly flush their excess nitrates.

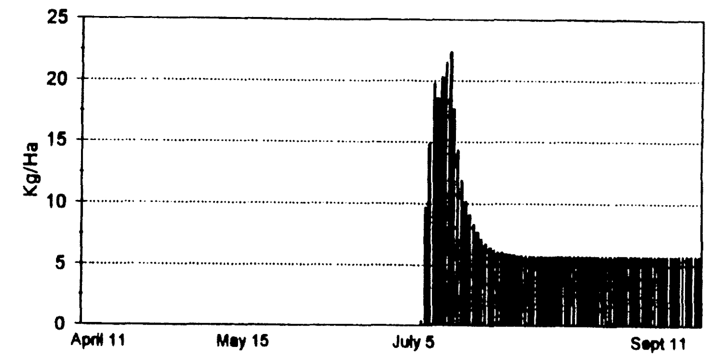


Graph 1 -- Field measures of nitrate leaching at 120 cm. compared with model generated estimate.

2. Anecdotal evidence from field experience.

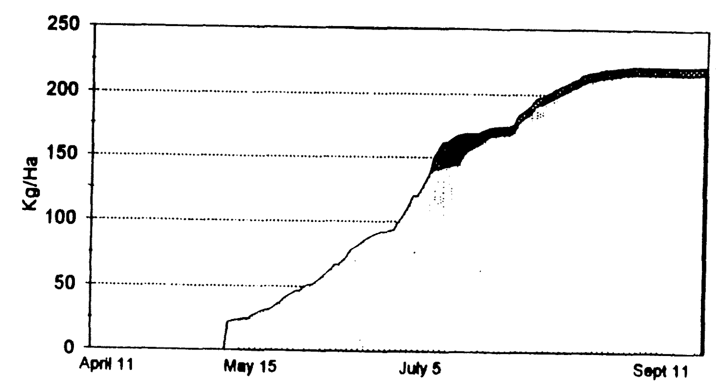
The second validation of model accuracy is the experience of early July. Just as the model was indicating a nitrogen deficiency stress in the crop, a similar warning was being given by the petiole sap test, administered by the Anoka Sand Plains staff. The grower was questioned about these assessments at the Becker field day on July 7th; he agreed that the crop was beginning to show signs of nitrogen stress, but was held off by weather (unti' 13th) from applying the fourth and final nitrogen application.

Graph 2 show the (simulated) crop stress response to a nitrogen deficiency, including the ability to bounce-back when sufficient nitrogen is subsequently applied. Between May 15th (emergence) and July 5th, the crop experienced no appreciable nitrogen stress. For the following 8 days, however, the simulated crop fell short of the reference crop potential nitrogen uptake by as much as 22 kg/ha. After nitrogen was applied by the grower on July 13th the crop made up much of its loss, but a permanent 6 kg/ha loss in total crop potential carried through the rest of the season.



Graph 2 -- Simulated crop nitrogen deficit totaled 6 kg/ha at season end.

Graph 3 shows the same effect, but in terms of total crop N uptake. Compared to the final crop N uptake of 220 kg/ha, the loss of 6 kg/ha in added potential uptake seems small (shaded area at top). But with a high value crop like potatoes, costs multiple rapidly; and the economics of high nitrogen inputs quickly becomes apparent. If the crop potential is 500 (100 lb.) bags, and in a good market they can bring (across the whole yield) 5 cents a lb., the total field value is $2,500per acre. A 2-percent yield reduction equals 10 bags or 1000 lbs, at a potentially cost the grower $50/acre. The growers marginal cost for nitrogen (or irrigation water for that matter) is negligible by comparison. As profit-maximizing agents, who wish to minimize the risk of yield loss from crop nitrogen stress, rational growers will continue to apply above optimal levels of fertilizer nitrogen and irrigation water.



C -- Total crop nitrogen plus stress loss of potential N uptake.

SECTION 3 > Alternative Simulation Results -- testing for better nitrogen and irrigation management options.

During the 1994 season, the grower reportedly applied 45 cm. of irrigation water to the field crop. Yet potatoes grown under similar conditions at the Becker experiment station, using Best Management Practices, needed only 25 cm. of irrigation. The strength of simulation modelling is the power to quickly and easily test alternative field scenarios. For instance, how would the nitrogen mass balance be changed if we assumed that the grower applied only half as much irrigation ?

Holding all other factors constant, table 5. shows the results of a simulation for which the amount of grower-supplied irrigation is cut in half -- 22.5 cm. instead of 45 cm. By definition, the nitrate contribution from the irrigator (measured at 22 ppm.) is also reduced by half -- to 55 kg/ha from 110 kg/ha. While total crop nitrogen uptake is unchanged at 220 kg/ha, the grower-supplied nitrogen now accounts for a greater portion (68%) of the total N uptake. Total nitrate leaching is reduced nearly 20-percent, both from the grower-supplied nitrogen and background sources.

Table 5. -- <u>Alternative 1.</u> Reduce irrigation schedule by one-half.

Total System Nitrogen Resources		
Grower-supplied N 290	Background nitrogen sources	<u>300</u>
	- initial active organic	215
	- initial inorganic profile	30
	- seasonal irrigation	55
Total Crop Nitrogen Uptake <220>		
Grower-supplied Crop N <150>	Background Crop N <70>	
Post-harvest Nitrogen Conditions		
Grower-supplied nitrogen	Background N sources	
- residual top mass <0>	- final active organic <115>	
- residual root <15>	- final Inorganic profile <35>	
- denitrification <10>	- denitrification <15>	
Total Nitrogen Leached @ 120 cm.		
Leachate <115>	Leachate <65>	

----- Units in Kg/Ha ---

A second alternative management strategy can also be easily tested using the simulation model. Could the grower have taken a nitrogen credit for the irrigation water and thereby reduced his level of fertilizer nitrogen applications ? Table 6. displays the results of simulating a 30 kg/ha credit for the irrigator N contribution, which translate into about a 10-percent reduction in the overall level of grower-supplied nitrogen. The combined affect of a 50-percent irrigation cutback and a 10-percent reduction in grower-supplied N, still fails to lower total crop N uptake below 220 kg/ha. Total nitrate leaching from the grower-supplied source, however, is reduced another 20-percent. Compared to the baseline scenario outlined in table 4., nitrate leaching could have been reduced by one-third, without negatively impacting crop development, had the grower cut irrigation by one-half and decreased his nitrogen applications by 10-percent. Both crop management changes would have been in line with (University of Minnesota) extension recommendations for best management practices.

Table 6. -- <u>Alternative 2.</u> Reduce irrigation by half and grower-supplied N by 10-percent.

Total System Nitrogen Resources		
Grower-supplied N 260	Background nitrogen sources	<u>300</u>
	- initial active organic	215
	- initial inorganic profile	30
	- seasonal irrigation	55
Total Crop Nitrogen Uptake <220>		
Grower-supplied Crop N <140>	Background Crop N <80>	
Post-harvest Nitrogen Conditions		
Grower-supplied nitrogen	Background N sources	
- residual top mass <0>	- final active organic <115>	
- residual root <15>	- final Inorganic profile <32>	
- denitrification <10>	- denitrification <13>	
Total Nitrogen Leached @ 120 cm.		
Leachate <95>	Leachate <60>	

----- Units in Kg/Ha ---

Part 2.

Activity:	Review the accuracy and information value of 1993 crop simulations by NCSWAP. Compare simulation data to field studies, and adjust model assumptions.
Outcome:	NCSWAP appeared to be over-estimated the soil water nitrate levels. Model adjustments resolved the problem, and predictive accuracy was improved. This period also saw improvements in the model's access to real-time climate data and nitrogen management decisions.
Period:	October 1993 through June 1994

Climatic summary statistics:
Preplant through harvest
April 14 – September 14

- **Climate summary:**

Total moisture : (rain plus irrigation)	72.2 cm	28.4 in.
Total pan evaporation:	18.3 cm	7.2 in.
Total degree days : (post emergence only)	1111 C	2032 F

- Climate data from the Becker experiment station, the Office of the State Climatologist, and the Soil Conservation Service SNOTEL system
- Degree days = average temperature - 10
- 1991 is the year of the model reference crop

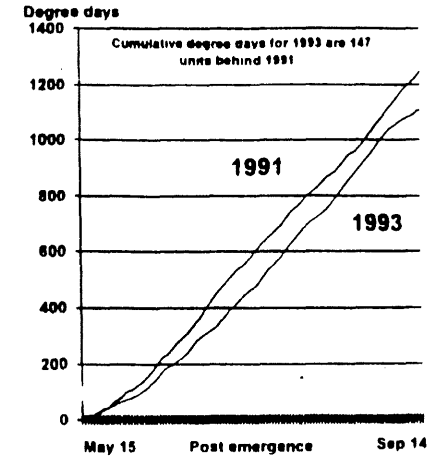


Fig. 1.1. **Climatic summary statistics.** -- Climatic conditions were one of four areas detailed in the Field Conditions Reports during the 1993 growing season. Growing degree days in 1993 remained below the 1991 reference crop baseline all season.

Moisture in the soil profile:
Preplant through harvest
April 14 -- September 14

- **Total moisture:**

	CM.	IN.
Initial profile H2O content:	16.4	6.5
Rain events plus irrigation:	72.2	28.4
Evapotranspiration:	(14.8)	(5.8)
Leaching at 144 cm:	(57.6)	(22.7)
Current profile H2O:	16.2	6.4

- There were 59 rain events over the 154 day period., totaling 62.2 cm. The average rain was just over 1cm., the largest event was 7.5 cm., Aug 27. Irrigation over 9 days added another 10 cms.

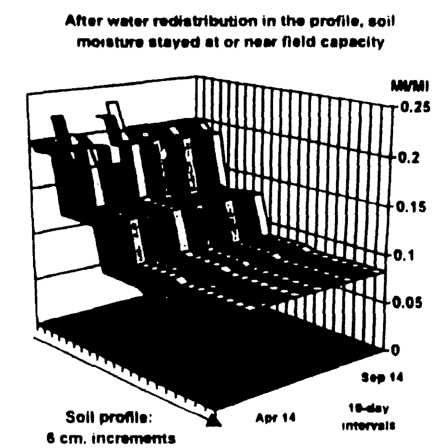


Fig. 1.2 **Moisture in the soil profile.** Steady rains through the 93 sea ... t soil moisture at or near field capacity according to the simulation model -- when ... ratio of soil water field capacity to water content at saturation was set at .48

Inorganic nitrogen in the soil profile:

Preplant through harvest
April 14 -- September 14

- Inorganic nitrogen summary:

	Kg N / Ha	Lb N / A
Initial profile content:	35	31
Applications: April 21	35	31
May 28	94	84
June 7	103	92
July 16-17	81	72
Total N applied	313	279
Irrigation (10cm @ 8 ppm)	7	6

- Conditions -- September 14

Plant uptake	(207)	(184)
Total net mineralization	129	115
Total denitrification	(12)	(11)
Leaching at 144 cm	(255)	(227)
Remainder in soil profile	10	9

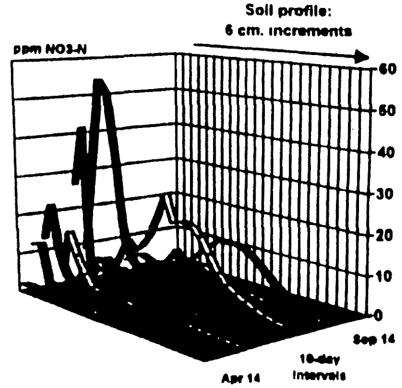


Fig. 1.3 **Inorganic nitrogen in the soil profile.** -- Water moved rather rapidly through the profile, taking nitrates with it -- the reduction factor for solute flow was set at .9. By the end of the 1993 season an estimated 255 kg/ha had leached from the profile.

Plant summary statistics:

Preplant through harvest
April 14 -- September 14

- Plant Summary:

Variety: Russet Burbank
Potential maximum yield: 17,000 Kg/Ha (15,181 Lb/A)

Planting date: April 20
Planting rate: 39,500 Plt/Ha [16,000 Plt/A]
Emergence: May 15
Full canopy: June 18
Harvest Sept. 11

- Current Plant Statistics -- Harvest

Dry matter: 16,750 Kg/Ha [14,908 Lb/A]
(tuber & vine)

Total plant N -- 207 Kg/Ha N [184 Lb/A]

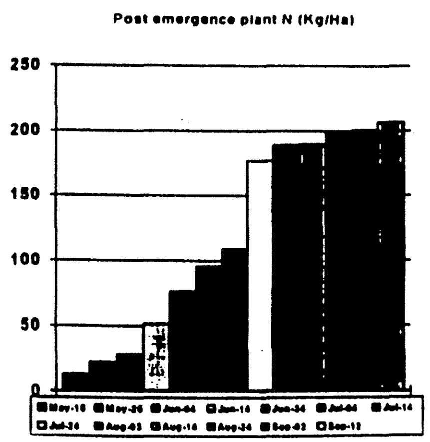


Fig. 1.4 **Plant summary statistics.** -- Maximum crop yield was set at 17,000 kg/ha in the beginning of the season in line with the growers expectations. The model estimated a near maximum potential yield as the 93 season ended. With a final plant (tuber and vine) nitrogen content of 1.3 percent. the crop took 207 kg/h N out of the soil profile.

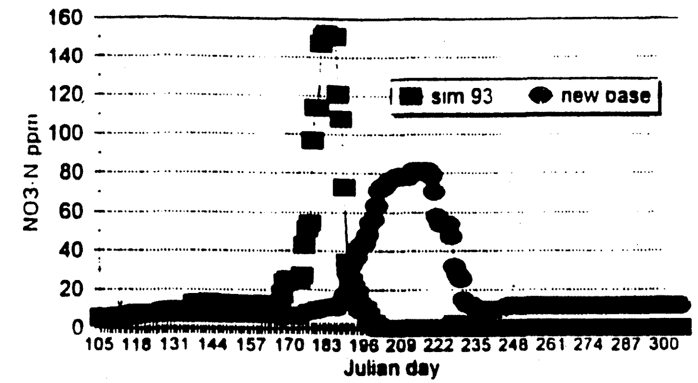


Fig. 2.1 ***Seasonal Predicted vs. New Baseline*** -- forecasts during the 93 season indicated higher than expected nitrate levels at a profile depth of 48". The new baseline is characterized by an increase from 48 to 55 percent water content at saturation. and a reduction in solute flows from .9 to .75. These have the effect of slowing the nitrate flow and keeping more H2O and N in the profile.

Moisture in the soil profile:

Preplant through harvest
April 14 -- September 14

Season 93

- Total moisture:

	CM.	IN.
Initial profile H2O content:	16.4	6.5
Rain events plus irrigation:	72.2	28.4
Evapotranspiration:	(14.8)	(5.8)
Leaching at 144 cm:	(57.6)	(22.7)
Current profile H2O:	16.2	6.4

New Baseline

Leaching at 144 cm:	(48.6)	(19.2)
Current profile H2O:	25.0	9.9

- There were 59 rain events over the 154 day period., totaling 62.2 cm. The average rain was just over 1cm., the largest event was 7.5 cm., Aug 27. Irrigation over 9 days added another 10 cms.

Fig. 2.2 ***Baseline vs. Season 93:*** Moisture in the soil profile -- comparing the 93-season simulation at year end with the new baseline model for soil moisture demonstrates the higher water holding capacity of the soil profile in the baseline

Plant summary statistics:

Preplant through harvest
April 14 -- September 14

- **Season 93:**

Variety:	Russet Burbank	
Potential maximum yield: 17,000 Kg/Ha	[15,181 Lb/A]	
Planting date:	April 20	
Planting rate:	39,500 Plt/Ha	[16,000 Plt/A]
Emergence:	May 15	
Full canopy:	June 18	
Harvest	Sept. 11	

- **New Baseline**

Variety:	Russet Burbank	
Potential maximum yield: 14,600 Kg/Ha	[13,038 Lb/A]	

- **Current Plant Statistics -- Harvest** (Season 93)

Dry matter: 16,750 Kg/Ha [14,908 Lb/A] (tuber & vine)

Total plant N -- 207 Kg/Ha N [184 Lb/A]

- **Current Plant Statistics -- Harvest** (New Baseline)

Dry matter: 14,560 Kg/Ha [13,002 Lb/A] (tuber & vine)

Total plant N -- 189 Kg/Ha N [169 Lb/A]

Fig. 2.3 ***Baseline vs. Season 93:*** Plant summary statistics -- plant N uptake is lower in the new baseline simulation do in part to the lower maximum crop yield assumption indicated by field data analysis. Maximum yield potential at season-end was 15-percent below grower expectations at the beginning of the season.

Inorganic nitrogen in the soil profile:

Preplant through harvest
April 14 -- September 14

- **Inorganic nitrogen summary:**

		Kg N / Ha	Lb N / A
Initial profile content:		35	31
Applications:	April 21	35	31
	May 28	94	84
	June 7	103	92
	July 16-17	81	72
Total N applied		313	279
Irrigation (10cm @ 8 ppm)		7	6

- **Season 93**
- **Conditions -- September 14**

Plant uptake	(207)	(184)
Total net mineralization	129	115
Total denitrification	(12)	(11)
Leaching at 144 cm	(255)	[illegible]
Remainder in soil profile	10	9

- **New Baseline**
- **Conditions -- September 14**

Plant uptake	(189)	(169)
Total net mineralization	129	115
Total denitrification	(12)	(11)
Leaching at 144 cm	(226)	(202)
Remainder in soil profile	41	37

Fig. 2.4 ***Baseline vs. Season 93:*** Inorganic N in the soil profile -- nitrate levels were 10-percent lower (at the 48" mark) under the new baseline model. Soil profile nitrogen levels calculated by the new baseline are more consistent with field analysis as well. Mineralization and denitrification did not change under the new baseline.

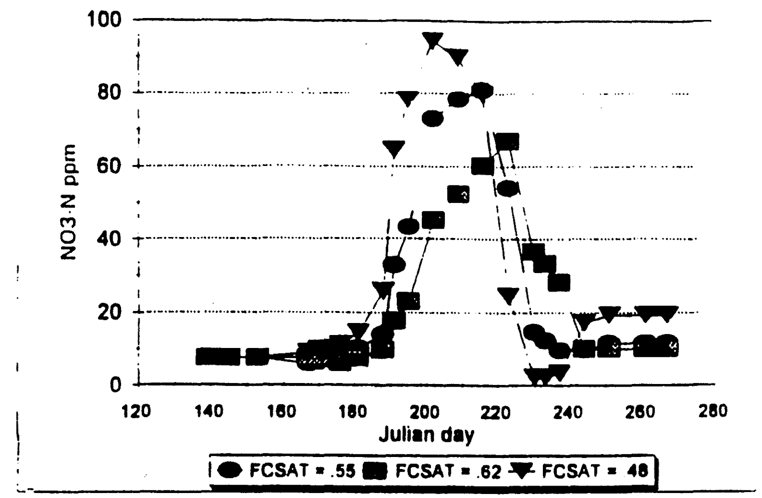


Fig. 2.5 ***Soil water concentrations given changes in field capacity ratio*** -- significant shifts in the soil water N concentrations at 48" reflect changes in the ratio of soil water field capacity to water content at saturation (FCSTAT) from .48 (season 93 assumption) to .55 (new baseline assumption).

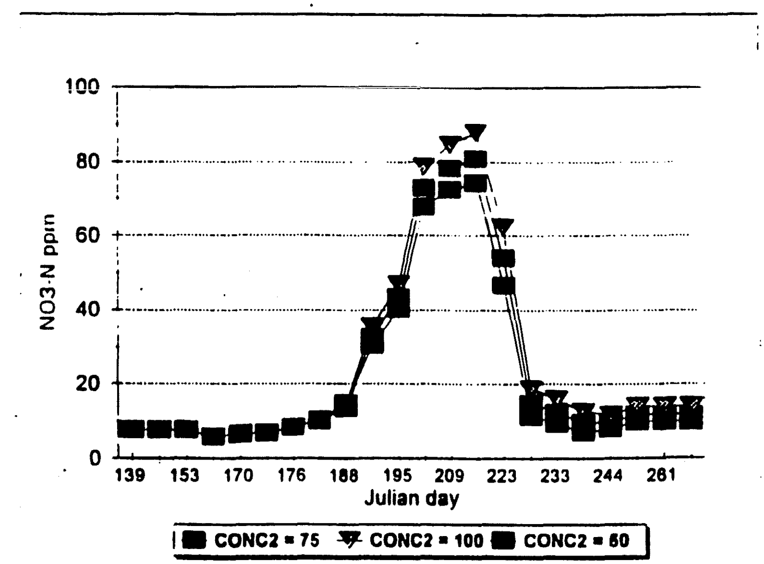


Fig. 2.6 ***Soil water concentrations given changes in potentially mineralizable N (N0)*** -- Less dramatic are the change brought on by altering N0 around the season 93 assumption of 75 kg/ha (CONC2). Consequently, this assumption was kept constant from the season 93 model to the new baseline model.

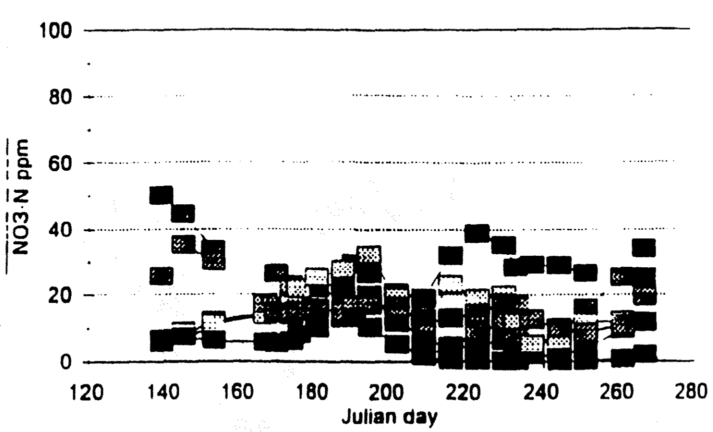


Fig. 3.1 **West side Within rows** -- Suction tube readings of soil water nitrates concentrations (at 48") within row tubes remained relatively low all season.

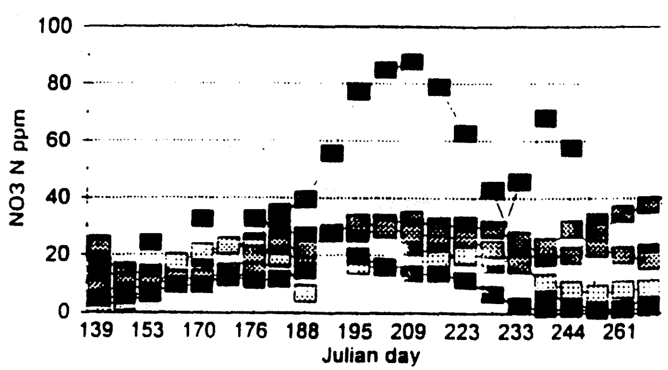


Fig. 3.2 **West side Between rows** --Suction tube readings between the rows average slightly higher most of the season, with an anomaly spike (from tube W3) as high as 85 ppm NO3-N.

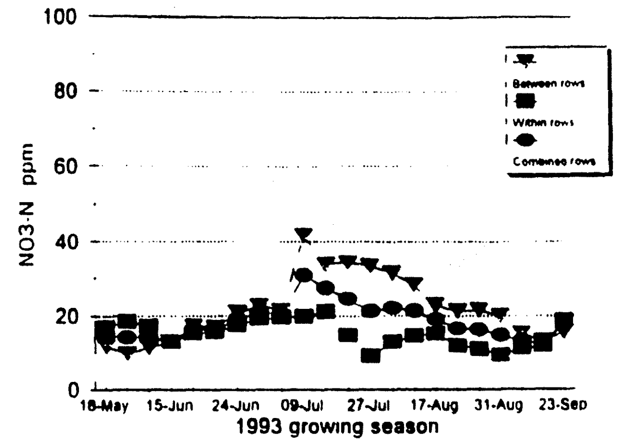


Fig. 3.3 **West side average rows** -- Averaged together the within and between row readings reached a maximum concentration (30 ppm) in early July.

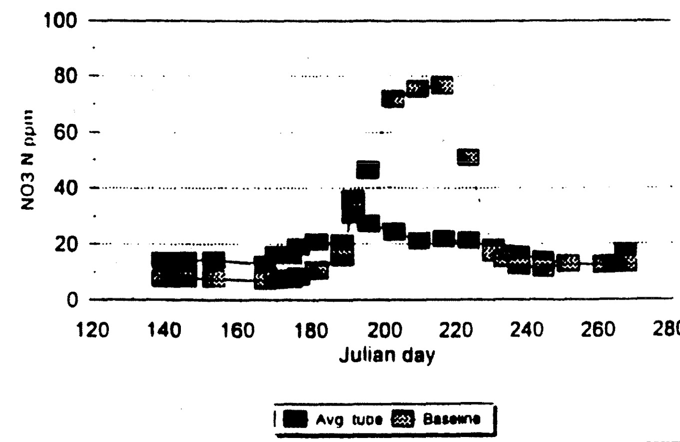


Fig. 3.4 **Average west side vs. baseline model** -- Compared to the average suction tube readings, the baseline simulation appears to over-estimate the soil water nitrate concentrations by as much as 3 fold.

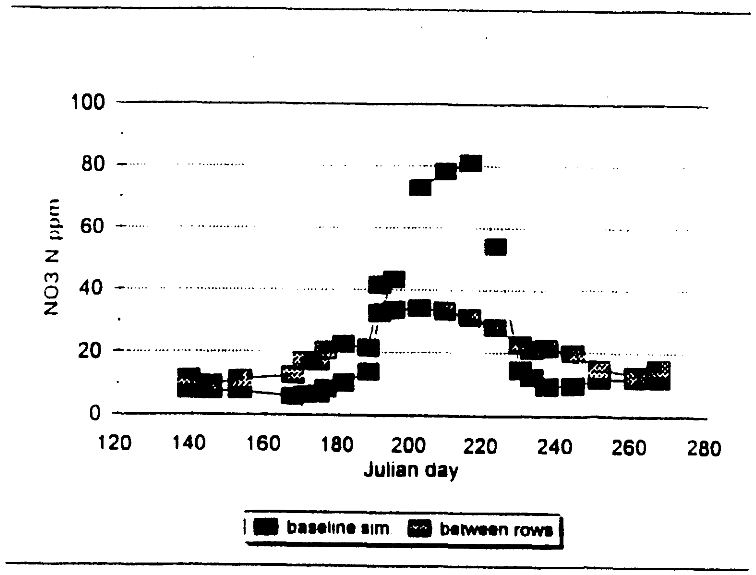


Fig. 3.5 ***Between rows average vs. baseline model*** -- Comparing the baseline model to the between row average only improves the fit modestly.

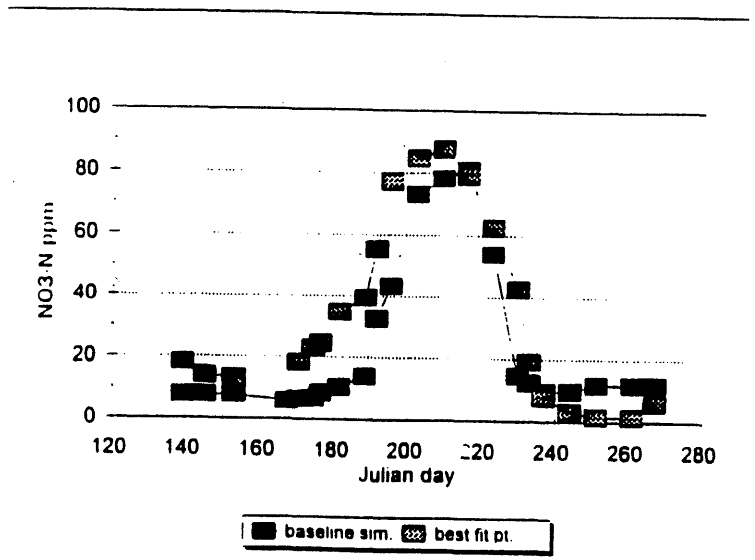


Fig. 3.6 ***Best fit data point vs baseline model*** -- If the baseline is compared to the single anomaly reading (W3) a near perfect fit appears.

Section 4. Comparing the new baseline to the East side suction tubes.

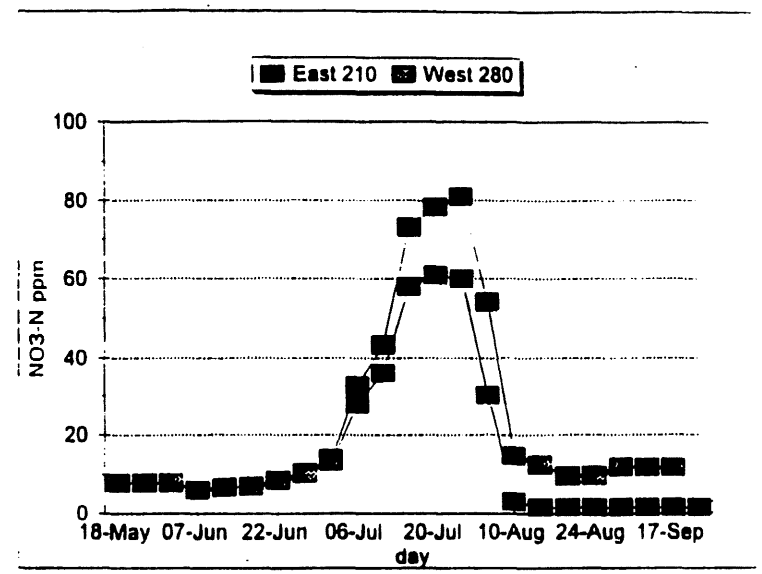


Fig. 4.1 ***Baseline soil water concentration comparison of East and West simulation*** -- A drop in soil water concentrations of 20 ppm (at the peak) was established by lowering the baseline nitrogen input by 70 kg/ha, to 210 kg/ha. No yield loss was predicted from this lower N input; consistent with trial estimates.

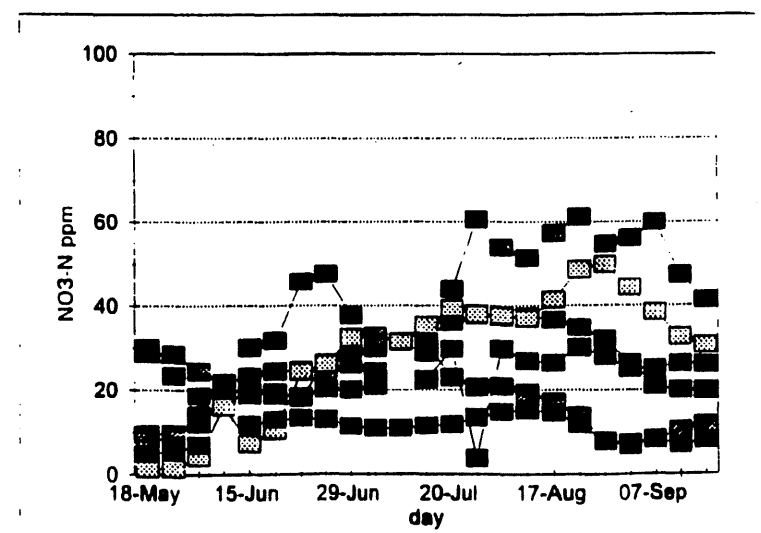


Fig. 4.2 ***East side Within rows*** -- Suction tube readings on the east side within rows seem a li[illegible]her than the west side, particularly near the end of the season.

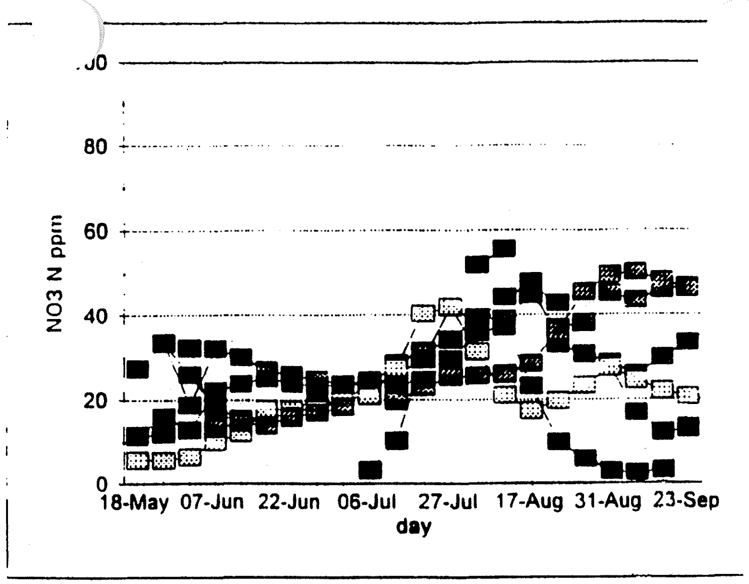


Fig. 4.3 ***East side Between rows*** -- Between row readings are a little more variable than within rows for the east side, with several readings spiking up in the late season.

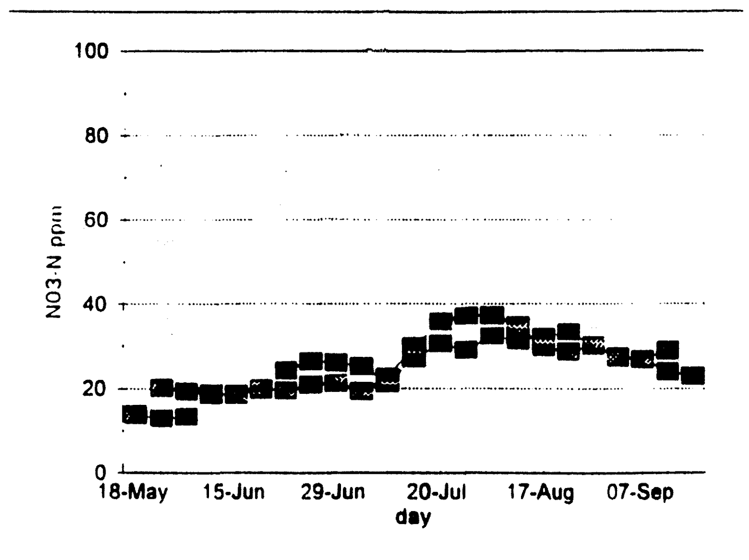


Fig. 4.4 ***East side average rows*** -- Unlike the west side, the average within and between row concentration readings stay very close throughout the growing season.

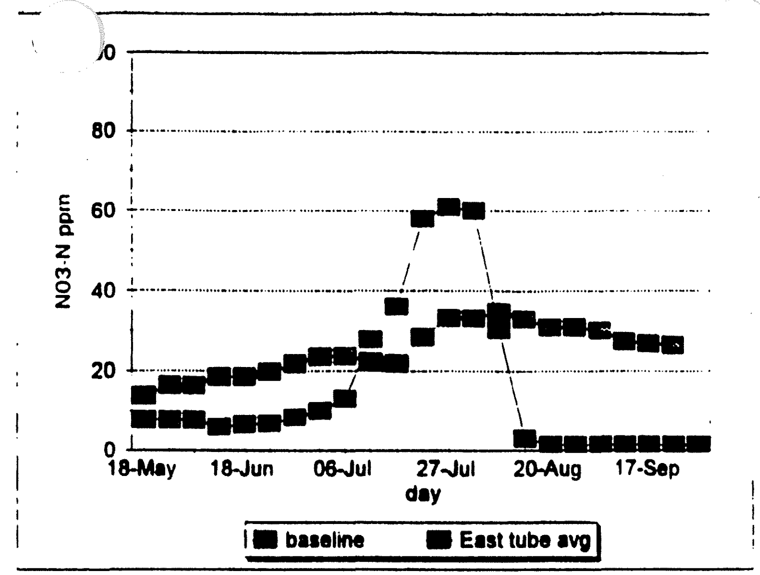


Fig. 4.5 ***East side suction vs baseline East*** -- As with the west side, the east side baseline model compared to the average suction tube reading does not make a very good fit.

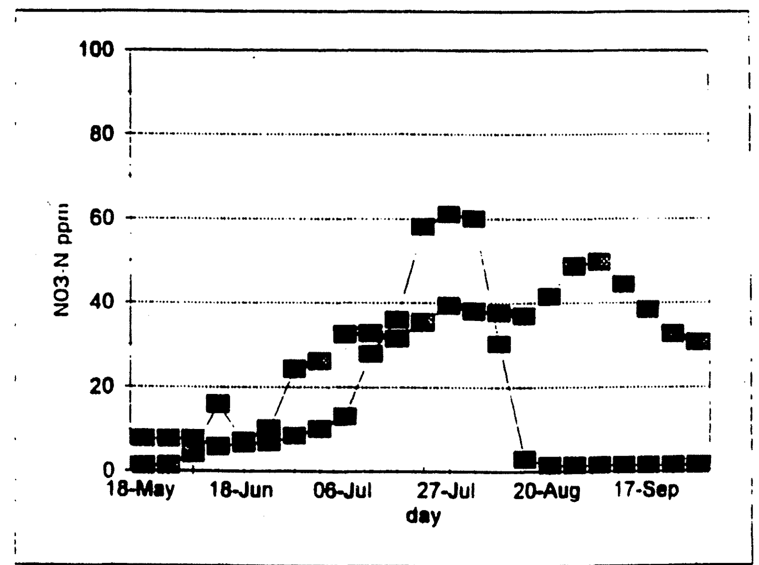
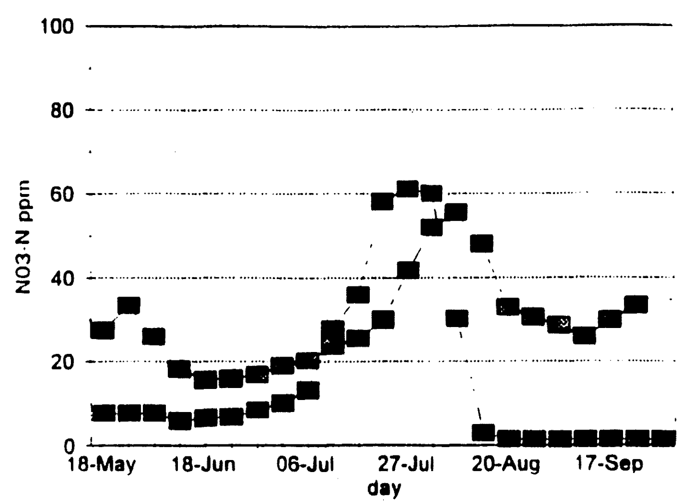
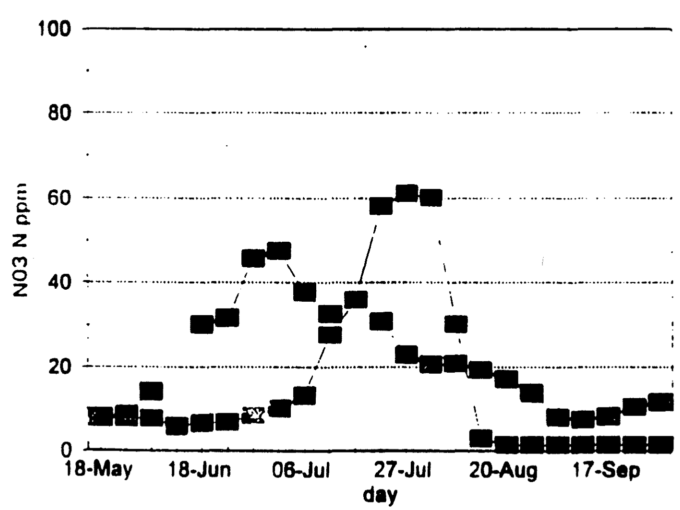


Fig 4.6-8 ***Three individual suction tubes vs baseline East*** -- Three tube readings compared to the east side baseline model show less of a fit than the anomaly on the west side.





Part 3.

Activity: Provide quick analysis of field conditions in a user friendly format. Organize simulations for prediction of soil moisture, plant nitrogen uptake, nitrate levels in the soil profile, and crop yield at four critical stages of crop development.

Outcome: Produced four simulations each season -- preplant, emergence, hilling, and harvest. Field condition reports were distributed and reviewed to kindred researchers, and nitrogen management recommendations were incorporated into the grower's ongoing strategy.

Period: April 1993 through June 1994

Simulation model results

of potato production at K & O farms,

Becker, Minnesota

Preplant through Harvest

April 14 -- September 14, 1993

1993 Field Conditions Report No. 4 -- 9/17/93

J.A.E. Molina and Barry Ryan
Soil Science Department, University of Minnesota

This project is funded in part by a grant from the Legislative Commission on Minnesota Resources

E4-14

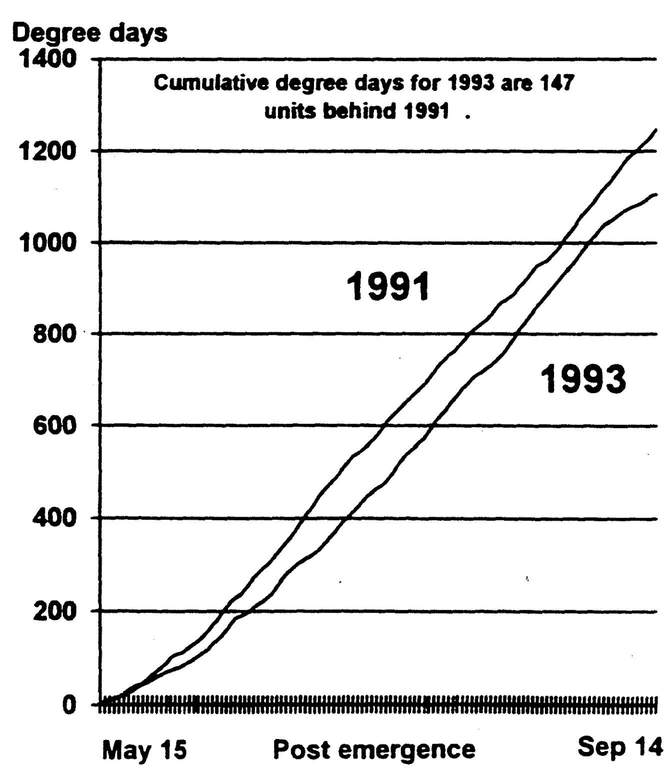
Climatic summary statistics:

Preplant through harvest
April 14 -- September 14

- **Climate summary:**

Total moisture : (rain plus irrigation)	**72.2 cm**	**28.4 in.**
Total pan evaporation:	**18.3 cm**	**7.2 in.**
Total degree days : (post emergence only)	**1111 C**	**2032 F**

- **Climate data from the Becker experiment station, the Office of the State Climatologist, and the Soil Conservation Service SNOTEL system**
- **Degree days = average temperature - 10**
- **1991 is the year of the model reference crop**



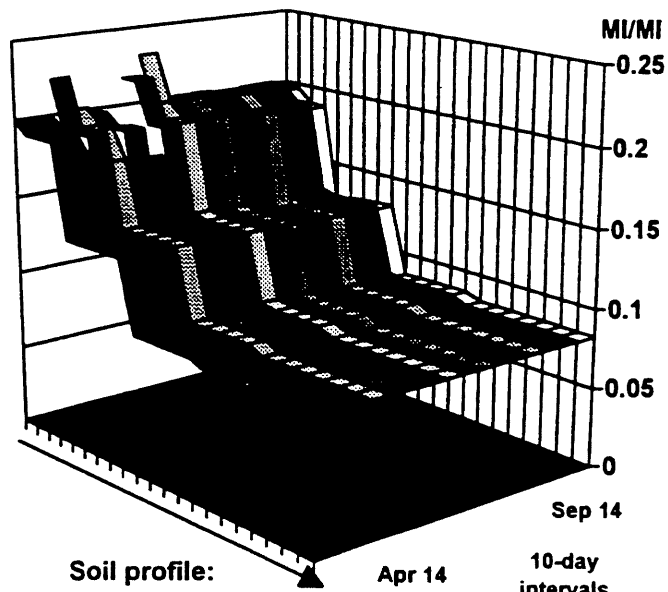
Moisture in the soil profile:
Preplant through harvest
April 14 -- September 14

- Total moisture:

	CM.	IN.
Initial profile H2O content:	16.4	6.5
Rain events plus irrigation:	72.2	28.4
Evapotranspiration:	(14.8)	(5.8)
Leaching at 144 cm:	(57.6)	(22.7)
Current profile H2O:	16.2	6.4

- There were 59 rain events over the 154 day period., totaling 62.2 cm. The average rain was just over 1cm., the largest event was 7.5 cm., Aug 27. Irrigation over 9 days added another 10 cms.

After water redistribution in the profile, soil moisture stayed at or near field capacity



E4-15

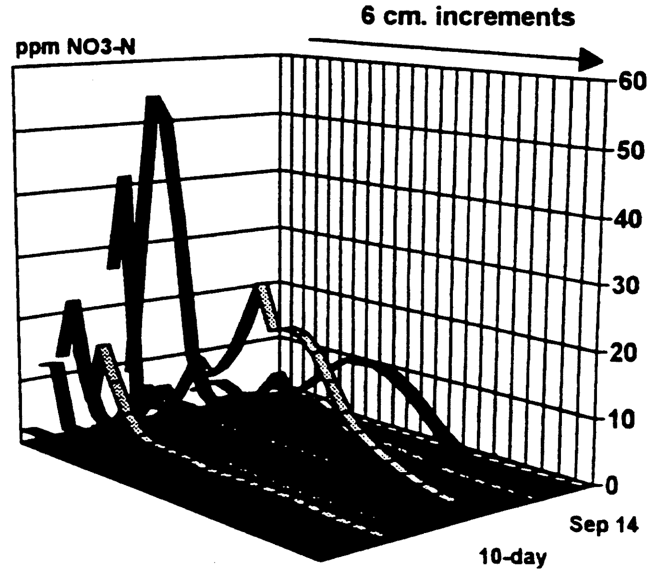
Inorganic nitrogen in the soil profile:
Preplant through harvest
April 14 -- September 14

- Inorganic nitrogen summary:

		Kg N / Ha	Lb N / A
Initial profile content:		35	31
Applications:	April 21	35	31
	May 28	94	84
	June 7	103	92
	July 16-17	81	72
	Total N applied	313	279
Irrigation (10cm @ 8 ppm)		7	6

- Conditions -- September 14

Plant uptake	(207)	(184)
Total net mineralization	129	115
Total denitrification	(12)	(11)
Leaching at 144 cm	(255)	(227)
Remainder in soil profile	10	9



Plant summary statistics:
Preplant through harvest
April 14 -- September 14

- **Plant Summary:**

Variety: Russet Burbank
Potential maximum yield: 17,000 Kg/Ha [15,181 Lb/A]

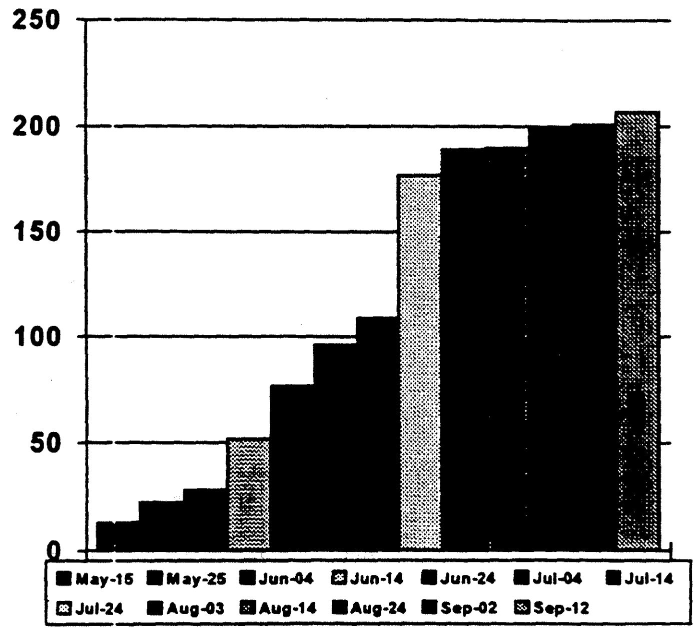
Planting date: April 20
Planting rate: 39,500 Plt/Ha [16,000 Plt/A]
Emergence: May 15
Full canopy: June 18
Harvest Sept. 11

- **Current Plant Statistics** -- Harvest

Dry matter: 16,750 Kg/Ha [14,908 Lb/A]
(tuber & vine)

Total plant N -- 207 Kg/Ha N [184 Lb/A]

Post emergence plant N (Kg/Ha)



E4-16

Simulation model results

of potato production at K & O farms,

Becker, Minnesota

Preplant through Early Maturity

April 14 -- August 14, 1993

1993 Field Conditions Report No. 3 -- 8/19/93

J.A.E. Molina and Barry Ryan
Soil Science Department, University of Minnesota

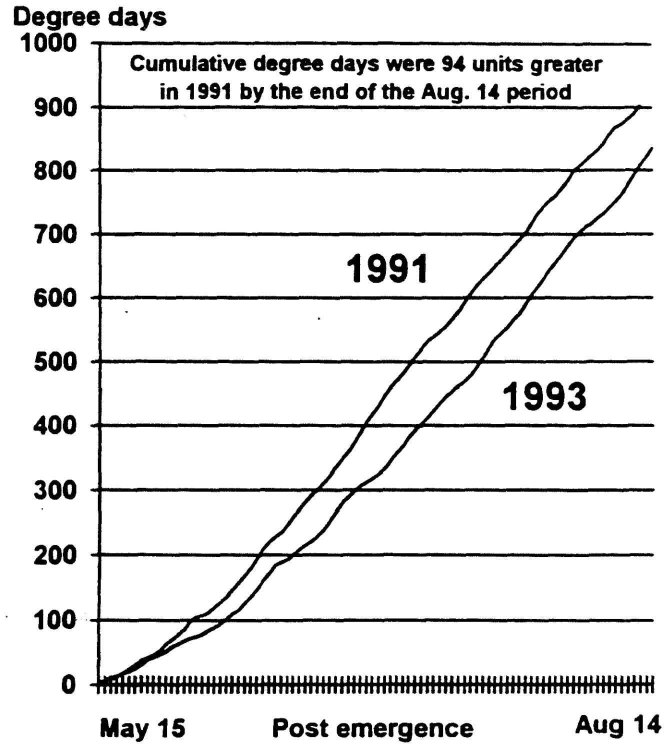
This project is funded in part by a grant from the
Legislative Commission on Minnesota Resources

Climatic summary statistics:
Preplant through early maturity
April 14 -- August 14

- **Climate summary:**

Total moisture : (rain plus irrigation)	**54.6 cm**	**21.5 in.**
Total pan evaporation:	**16.7 cm**	**6.6 in.**
Total degree days : (post emergence only)	**822 C**	**1512 F**

- Climate data from the Becker experiment station, the Office of the State Climatologist, and the Soil Conservation Service SNOTEL system
- Degree days = average temperature - 10
- 1991 is the year of the model reference crop



E4-17

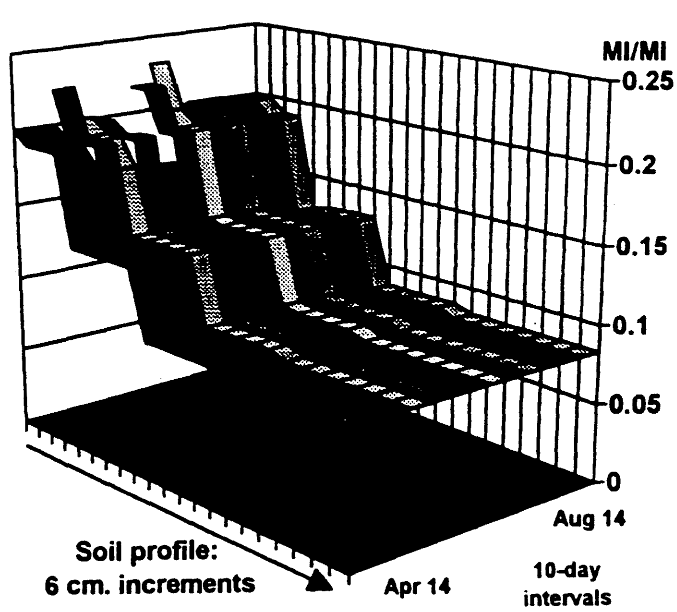
Moisture in the soil profile:
Preplant through early maturity
April 14 -- August 14

- **Total moisture:**

	CM.	IN.
Initial profile H2O content:	16.4	6.5
Rain events plus irrigation:	54.6	21.5
Evapotranspiration:	(13.7)	(5.4)
Leaching at 144 cm:	(41.1)	(16.2)
Current profile H2O:	16.2	6.4

- **Over the 123 day simulation period there have been 52 rain events totaling 45.2 cm. plus 8 days of irrigation totaling 9.4 cm. The average rain event was 1.25 cm., the largest event was just over 4 cm., July 16.**

After water redistribution in the profile, soil moisture stayed at or near field capacity



Plant summary statistics:
Preplant through early maturity
April 14 -- August 14

- **Plant Summary:**

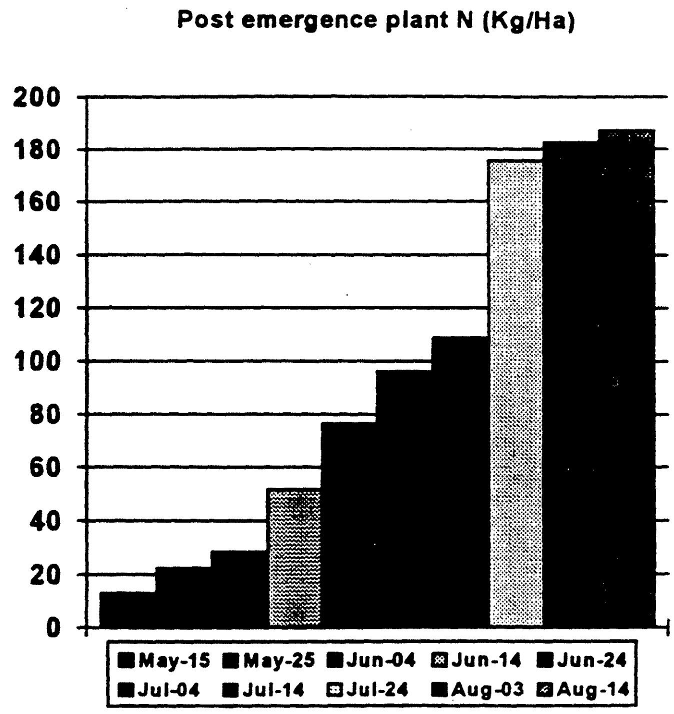
Variety: Russet Burbank
Potential maximum yield: 17,000 Kg/Ha [15,181 Lb/A]

Planting date: April 20
Planting rate: 39,500 Plt/Ha [16,000 Plt/A]
Emergence: May 15
Full canopy: June 18

- **Current Plant Statistics** -- August 14

Dry matter: 14,170 Kg/Ha [12,654 Lb/A]
(tuber & vine)

Total plant N -- 188 Kg/Ha N [168 Lb/A]



E4-18

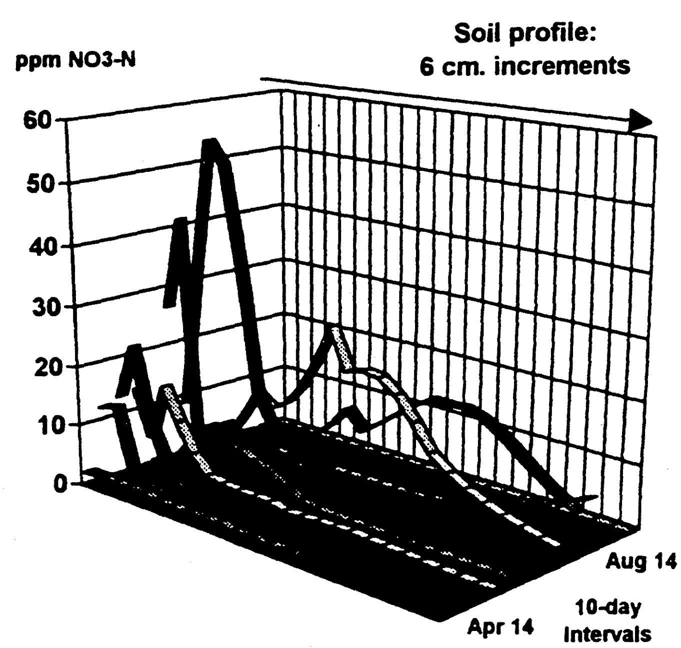
Inorganic nitrogen in the soil profile:
Preplant through early maturity
April 14 -- August 14

- **Inorganic nitrogen summary:**

		Kg N / Ha	Lb N / A
Initial profile content:		35	31
Applications:	April 21	35	31
	May 28	94	84
	June 7	103	92
	July 15	56	50
Total N applied		288	257
Irrigation (9cm @ 8 ppm)		4	3

- **Conditions -- July 14**

	Kg N / Ha	Lb N / A
Plant uptake	(188)	(168)
Total net mineralization	112	100
Total denitrification	(13)	(12)
Leaching at 144 cm	(242)	(216)
Remainder in soil profile	4	3



Simulation model results

of potato production at K & O farms,

Becker, Minnesota

Preplant through full canopy plus 26 days

April 15 -- July 14, 1993

1993 Field Conditions Report No. 2 -- 8/5/93

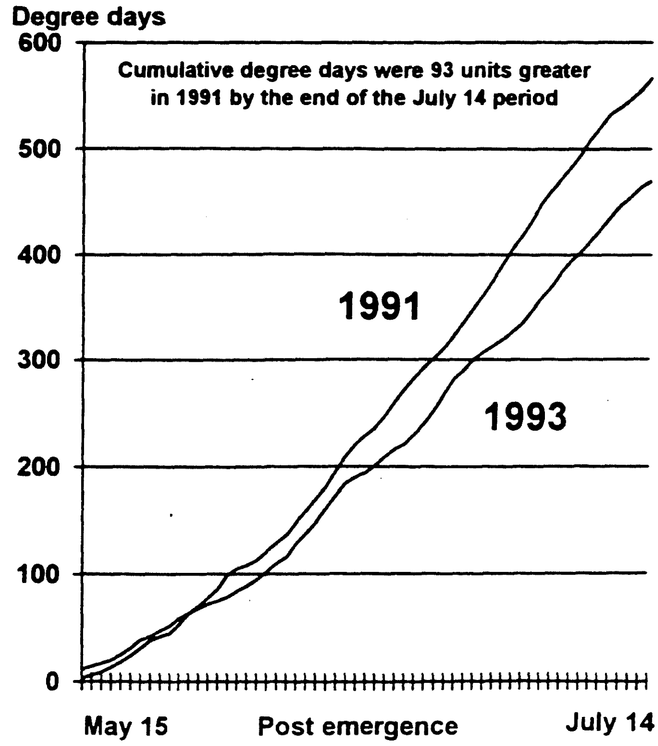
J.A.E. Molina and Barry Ryan
Soil Science Dpeartment, University of Minnesota

This project is funded in part by a grant from the Legislative Commission on Minnesota Resources

Climatic summary statistics:
Preplant through full canopy plus 26 days
April 14 -- July 14

- <u>**Climate summary:**</u>

Total moisture : (rain plus irrigation)	**38.2 cm**
Total pan evaporation:	**15.2 cm**
Total degree days : (post emergence only)	**470**



- **Climate data from the Becker experiment station, the Office of the State Climatologist, and the Soil Conservation Service SNOTEL system**
- **Degree days = average temperature (C) - 10**
- **1991 is the year of the model reference crop**

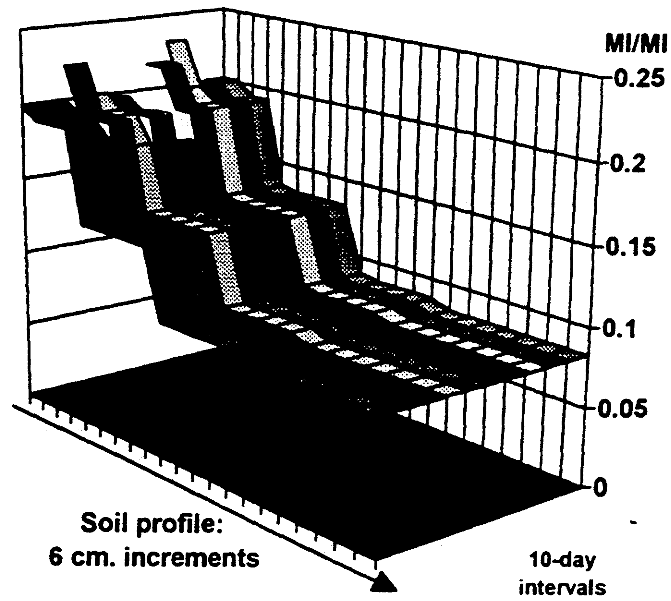
Moisture in the soil profile:

Preplant through full canopy plus 26 days
April 14 -- July 14

- **Total moisture:**

Initial profile H2O content:	16.4 cm
Rain events plus irrigation:	40.3 cm
Evapotranspiration:	(12.1 cm)
Leaching at 144 cm:	(28.0 cm)
Current profile H2O content:	16.6 cm

After water redistribution in the profile, soil moisture stayed at or above field capacity



Inorganic nitrogen in the soil profile:

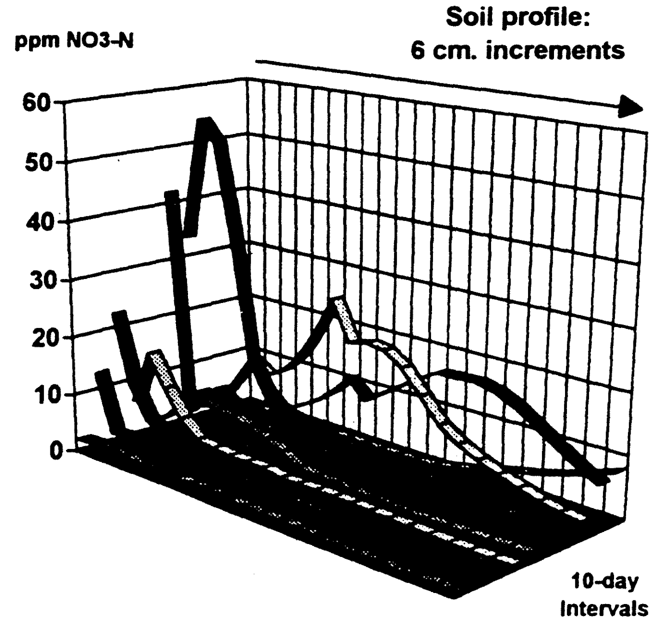
Preplant through full canopy plus 26 days
April 14 -- July 14

- **Inorganic nitrogen summary:**

		Kg N / Ha
Initial profile content:		35
Applications:	Apr 21	35
	May 28	94
	Jun 7	103
Total N applied		232
Irrigation (7cm @ 8 ppm)		3

- **Conditions -- July 14**

Plant uptake	(109)
Total net mineralization	90
Total denitrification	(9)
Leaching at 144 cm	(230)
Remainder in soil profile	12

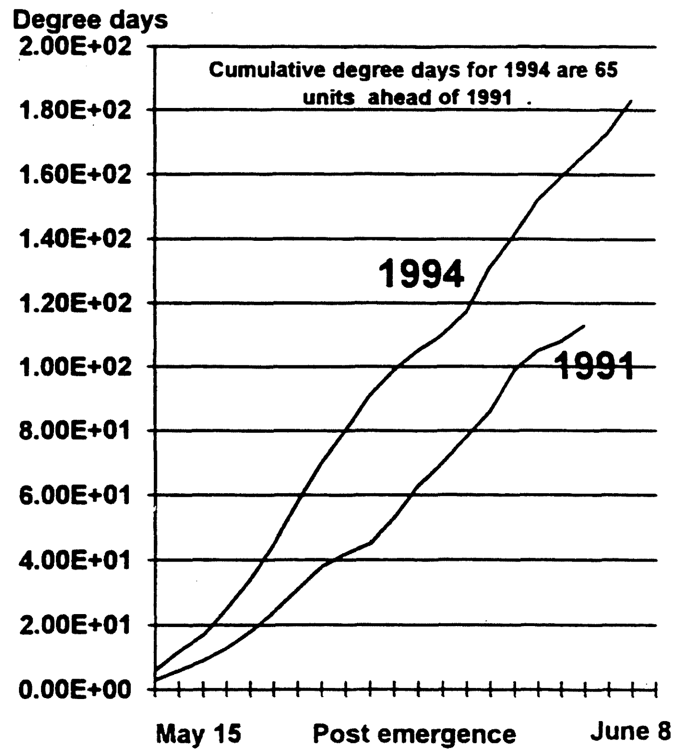


Climatic summary statistics:
Pre-plant through post-emergence
April 11 - June 8

- Climate summary:

Total moisture : (rain plus irrigation)	17.1cm	6.7 in.
Total pan evaporation:	4.3 cm	1.7 in.
Total degree days : (post emergence only)	183 C	361 F

- Climate data from the Becker experiment station, the Office of the State Climatologist, and the Soil Conservation Service SNOTEL system
- Degree days = average temperature - 10
- 1991 is the year of the model reference crop



E4-21

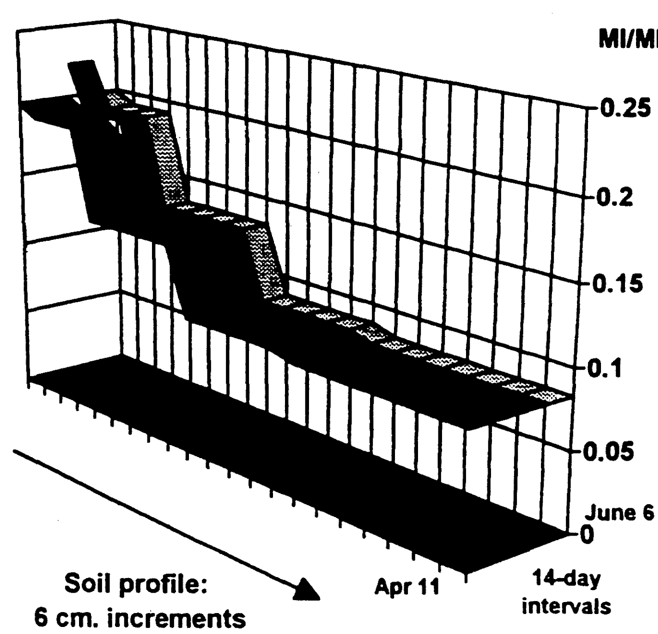
Moisture in the soil profile:
Pre-plant through post-emergence
April 11 -- June 8

- Total moisture:

	CM.	IN.
Initial profile H2O content:	26.8	10.5
Rain events plus irrigation:	17.1	6.7
Evapotranspiration:	(4.1)	(1.6)
Leaching at 144 cm:	(11.4)	(4.5)
Current profile H2O:	28.4	11.0

- There have been 11 rain events over the 54 day period., totaling 13.1 cm. The average rain was just over 1cm., the largest event was 3.1 cm. Irrigation over 2 days added another 4 cms.

After water redistribution in the profile, soil moisture stayed at or near field capacity



Plant summary statistics:
Preplant through full canopy plus 26 days
April 14 -- July 14

- **Plant Summary:**

Variety: Russet Burbank
Potential maximum yield of 17,000 Kg/Ha

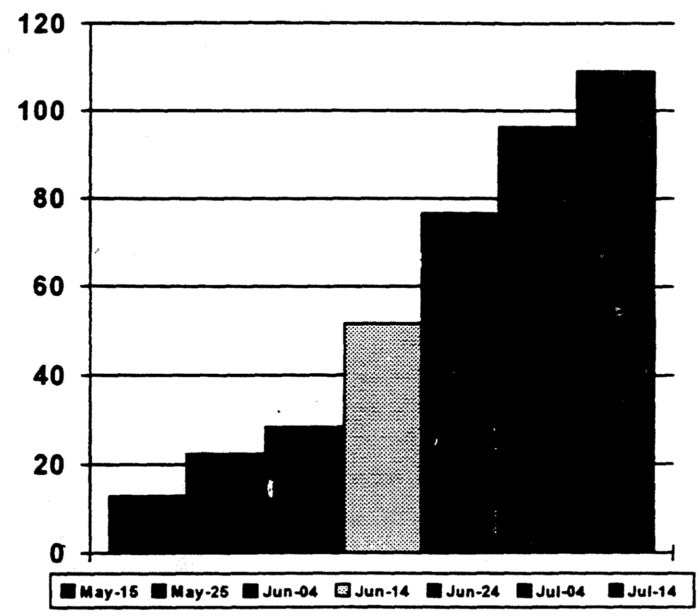
Planting date: April 20
Planting rate: 39,500 Plt/Ha
Emergence: May 15
Full canopy: June 18

- **Current Plant Statistics** -- July 14

Top mass dry matter: 4334 Kg/Ha (tuber & vine)

Total plant nitrogen -- 109 Kg/Ha N

Post emergence plant N (Kg/Ha)



E4-22

Simulation model results
of potato production at K & O farms,
Becker, Minnesota

Pre-plant through Post-emergence
April 11 -- June 8, 1994

1994 Field Conditions Report No. 1 -- 6/9/94

J.A.E. Molina and Barry Ryan
Soil Science Department, University of Minnesota

Funding for this project approved by the Minnesota Legislature, ML 1993, Chapter 172, Sec. 14, Subd. __, as recommended by the Legislative Commission on Minnesota Resources

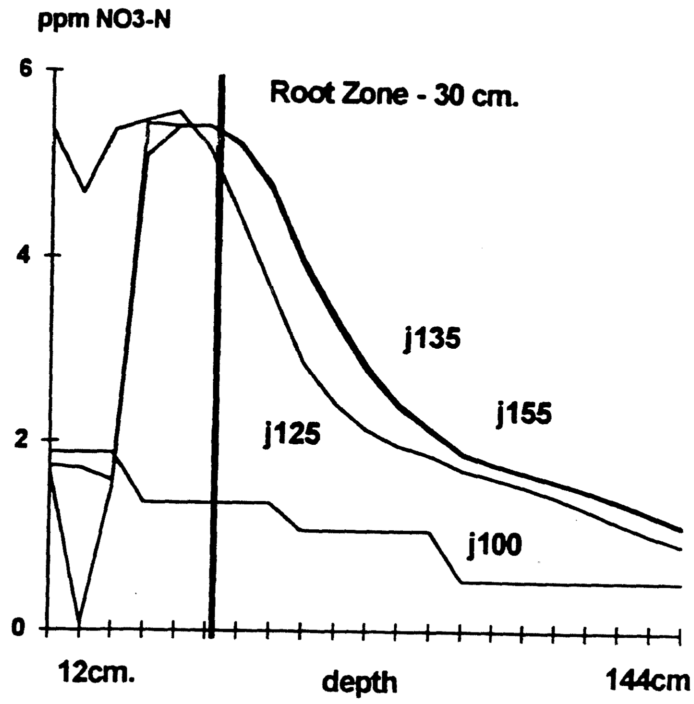
Inorganic nitrogen in the soil profile:
Pre-plant through post-emergence
April 11 -- June 8

- Inorganic nitrogen summary:

		Kg N / Ha	Lb N / A
Initial profile content:		35	31
Application:	April 12 (j101)	27	24
	May 25 (j143)	94	85
Total N applied		131	117
Irrigation (3cm @ 8 ppm)		2	2

- Conditions -- June 8 (j157)

	Kg N / Ha	Lb N / A
Plant uptake	(50)	(44)
Total net mineralization	30	27
Total denitrification	(.5)	(.4)
Leaching at 144 cm	(6)	(5)
Remainder in soil profile	132	118



E4-23

Plant summary statistics:
Pre-plant through post-emergence
April 11-- June 8

- Plant Summary:

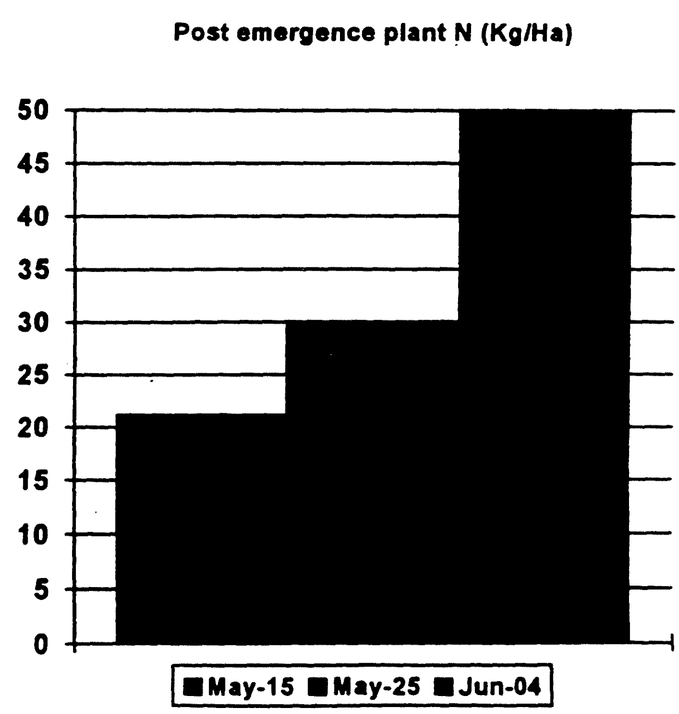
Variety: Russet Burbank
Potential maximum yield: 17,000 Kg/Ha [15,181 Lb/A]

Planting date: April 12
Planting rate: 39,500 Plt/Ha [16,000 Plt/A]
Emergence: May 15

- Current Plant Statistics -- post-emergence

Dry matter: 1030 Kg/Ha [917 Lb/A]
(tuber & vine)

Total plant N -- 50 Kg/Ha N [44.5 Lb/A]
Nitrogen deficit : 4 Kg/Ha [3.5 Lb/A]



F. Title of objective: Disseminate information.

F.1. Activity: Develop a network of on-farm demonstrations to serve as the core for the educational effort.

F.1.a. Context with the project: One of the most effective methods for disseminating management information to farmers is quality, local, on-farm demonstrations.

F.1.b Methods: The core of this educational program is five strategically placed on-farm demonstrations of tillage and fertilizer or manure management strategies to reduce and/or make more efficient use of nitrogen for corn, alfalfa or potato. Plots will be large to accommodate and simulate cooperators' operations and designed in a randomized complete block or split plot design with three replications. Treatments and crop responses will be characterized in enough detail to determine probable cause and effect on yield differences and inputs tallied to assess influences on profitability. Data collected from growers' fields on nitrate movement will be used to allow comparison of how management practices affect nitrate losses and crop production.

Nitrate-N will be determined in soil and water samples collected at various depths through the growing season at two demonstration sites.

Field days will be scheduled at each demonstration site.

F.1.c. Materials: Materials necessary to accomplish this activity will consist of: I) farm equipment, seed, fertilizer/manure supplied by farmer cooperators; II) suction tubes, sample bottles and bags, use of existing assorted laboratory equipment for analyzing soil, water, plant tissue and manure samples; III) scales for determining manure application rates, data forms, field markers, tape measure, other plot related miscellany, fact sheets, field maps and advertising flyers.

F.1.d. Budget: $45,000, **Balance:** $0

F.1.e. Timeline:

	7/93	1/94	6/94	1/95	6/95
Identify cooperators	xxxx				
Assess farming operation and design demonstration	xxxx				
Implement demonstrations and collect data			xxxx		xxxx
Field tours held in cooperation with local agency advisors			xxxx		xxxx

F.1.f. Status: Five on-farm demonstrations of efficient nitrogen and manure management were held in the north central sands region. Three demonstrations focused on manure management (two in corn and one in edible beans). A fourth demonstration looked at refining split applications of nitrogen in potato. The fifth demonstration looked at deep tillage and N source in a soil with a compacted Bt layer.

The manure demonstrations proved to be a good learning tool both for the growers and the support staff. Manure application rates were substantially reduced through the process of manure testing and spreader calibration.

The complexity of the manure issue was highlighted in this project. By doing the demonstrations on-farm, a whole-farm component is automatically introduced into each management practice being demonstrated. The Myron Quaal farm and the Marvin Runyan farm, although they are both dairies and only ten miles apart on sandy soils, provided very different responses to recommended manure management. This was primarily due to differing attitudes toward the value of corn and how the crop fits in their farm structure. The Tobkin edible bean manure demonstration again showed that the manure issue must be addressed within a whole-farm perspective. Refining manure application rates may be of secondary importance when compared to the potential for the manure to improve bean root health.

Overall, the manure demonstrations provided good local examples of refined manure management practices. There is strong interest in these communities to use this information to save money on fertilizer where manure is already being spread. The demonstrations showed that manure can be a dependable, environmentally sound sole source of nitrogen when combined with lab analysis and spreader calibration.

The John Moyer potato nitrogen demonstration showed that John was able to achieve higher yields and reduced nitrate leaching by reducing nitrogen rates in the starter and timing his late applications with the use of the petiole sap nitrate test.

The John Moyer deep tillage and nitrogen source demonstration suggested that the deep tillage improved rooting depth two years after the tillage was performed. There was no evidence that deep tillage increased nitrate leaching potential.

F.2. Activity: Produce demonstration data summaries and conduct workshops for farmers and field staff of local agencies.

F.2.a. Context within the project: Information from the on-farm demonstrations and other project objectives will be summarized to allow growers to compare how their practices affect nitrate movement and production and to encourage adoption of new guidelines that will decrease losses of nitrate nitrogen while maintaining profitable farming operations. Joint training of field staff of the Minnesota Extension Service, the Soil Conservation Service, and Soil and Water Conservation Districts will greatly multiply the information dissemination efforts by using "in place" agency field staff as vehicles for information transfer.

F.2.b. Methods: All cooperators, including farmers, will meet to evaluate the data collected and to determine the program for farmer and field staff workshops. Decisions on number and location of the programs will be made at that time. Presentations from both farmer cooperators and researchers will be included. Data from the demonstrations and other research components will be summarized into workshop presentation materials and fact sheets for general distribution in the North-Central Sands area.

F.2.c. Materials: Audio/visual aids and printed materials.
F.2.d. Budget: $10,000, **Balance:** $0
F.2.e. Timeline:

	7/93	1/94	6/94	1/95	6/95
Prepare data summaries	xxxx		xxxx		
Field staff training	xxxx		xxxx		
Farmer training workshops	xxxx		xxxxxxxxx		

F.2.f. Status: Data summaries for all the demonstrations have been completed and reviewed with the farmer cooperators and support staff. Further meetings are in progress to expand the manure issue to the level of soil quality/health.

Objective F. Disseminate information.

F.1. Activity: Develop a network of on-farm demonstrations to serve as the core for the educational effort.

F.1.a. Context within the project: One of the most effective methods for disseminating management information to farmers is quality, local, on-farm demonstrations. Demonstrations offer the opportunity for farmers to see research results from numerous sources integrated into management and cropping systems designed for and utilized by farmers with similar enterprises and geographic/soil characteristics. The adoption of new guidelines presented in the on-farm demonstrations will likely decrease losses of nitrate nitrogen while maintaining profitable farming operations.

F.1.b. Methods: The core of this educational program consisted of five strategically placed on-farm demonstrations of tillage. fertilizer and manure management strategies to reduce and/or make more efficient use of nitrogen for corn, potato and edible beans. Cooperators were identified through County Extension Agents, Soil Conservation Service District staff, Soil and Water Conservation Service staff and through previous participation in on-farm demonstrations. Cooperators and sites were evaluated for demonstration suitability by on-site visits. Plots were large enough to accommodate and simulate cooperators' operations and designed in a randomized complete block design with three or four replications. Treatments and crop responses were characterized in enough detail to determine probable cause and effect on yield differences. Data collected from growers' fields on nitrate movement were used to allow comparison of how management practices affect nitrate losses and crop production. A detailed description of the design of each demonstration is presented in the appendix below.

Three demonstrations focused on the more efficient use of organic nitrogen sources. Using cooperator manure and soil testing records, manure was applied for a base of approximately 90 to 120 pounds of N available for the corn or edible bean crop. One demonstration assessed various split applications of nitrogen on potatoes. one demonstration looked at the affect of deep tillage and nitrogen source on the potential for nitrate leaching.

F.1.c. Materials: Materials necessary to accomplish this activity consisted of: i) farm equipment, seed, fertilizer/manure supplied by farmer cooperators; ii) suction tubes, sample bottles and bags, use of existing assorted laboratory equipment for analyzing soil, water, plant tissue and manure samples; iii) scales for determining manure application rates, data forms, field markers, tape measure, other plot related miscellany, fact sheets, field maps and advertising flyers.

F.1.d. Budget: $45,000
Remaining: $0.00

F.1.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Identify cooperators	****				
Assess farming operation and design demonstration	****				
Implement demonstrations and collect data			****		****
Field tours held in cooperation with local agency advisors			****		****

F.1.f. Status: Five on-farm demonstrations of efficient nitrogen and manure management have been successfully completed. Field days were held at each of the five demonstration sites in July, 1994. All cooperators, including farmers, met to evaluate the data collected. Data from the demonstrations have been summarized into workshop presentation materials. Fact sheets will be complete by the end of June and presented at a meeting in Perham in the first week of July.

F.1.g. Appendix:

Demonstration Designs

Five on-farm nitrogen management demonstrations were held in the North-Central sands region of Minnesota in 1993-94. Three demonstrations focused on manure management (two in corn and one in edible beans). A fourth demonstration looked at refining split applications of nitrogen in potato. The fifth demonstration looked at deep tillage and N source in a soil with a compacted Bt layer.

The three manure demonstrations included the Marvin Runyan dairy farm south of Verndale, The Myron Quaal dairy farm northwest of Staples and the Tobkin edible bean farm in Perham. The purpose was to show the effectiveness of manure as a nitrogen source by promoting proper manure nutrient testing, estimation of nutrient availability, and spreader calibration. Yields in manured corn and beans were compared to yields fertilized with conventional rates of synthetic nitrogen.

The following demonstration design was used at all three manure study sites. Twelve adjacent field-size plots (300 ft. long strips), planted and harvested with standard farm equipment, were fertilized with four nitrogen treatments: a no nitrogen control, half rate manure, full rate manure (both according to manure lab analysis), and a conventional rate of commercial nitrogen. The experimental design was a randomized, complete block with three replications and four treatments.

The sampling regime focused on the dynamics of the nitrogen status of the crop and soil through the season as well as grain yield and quality. The assessment of nitrogen dynamics included in-season measurement of soil mineral nitrogen, corn ear leaf nitrogen at silk, and basal stalk nitrogen (corn stalk from 6-14" above ground) at harvest.

The corn ear leaf samples were taken as a standard assessment of the nitrogen status of the corn at the critical point of movement of nitrogen to the grain. The basal stalk samples were taken to test for the amount of excess residual nitrogen not translocated to the grain. It is assumed that a high level of nitrogen in the basal stalk may reflect excess mineral nitrogen in the soil at the end of the season which would be susceptible to leaching. Grain quality was assessed by measuring grain moisture, test weight and protein.

Edible bean roots at harvest showed a marked difference between treatments so root length was quantified by grid intersection.

The John Moyer tillage demonstration, two miles southwest of Verndale, compared tillage practices and nitrogen forms in irrigated corn (1993) and the effect of tillage on edible bean root development (1994) on a Verndale sand with strong Bt horizon.

Nitrate-N was determined in soil at various depths and water samples at a depth of three feet collected through the growing season at the tillage and the potato demonstration sites. The main plots were conventional moldboard plowing with and without deep tillage using a paraplow with subplots comparing anhydrous ammonia and 28% nitrogen sources. Suction tube water samples were taken weekly or the day after a 1" rain or irrigation event. Additional measurements taken include: yield, grain nitrogen and basal stalk nitrogen.

To emphasize late season nitrogen application and de-emphasize early season application, the John Moyer potato demonstration (three miles northeast of Staples) compared conventional nitrogen management in potato (Moyer's sidedress plan) with low nitrogen starter plus increased late sidedress and low nitrogen starter plus sidedress based on the petiole sap test. Tissue nitrogen at weekly intervals during the growing season were determined using the petiole sap test. Potato total yields and quality by size were taken to indicate success of the sap test based sidedress plan.

Marvin Runyan Manure Rate on Corn Demonstration

Marvin raises corn, oats and alfalfa hay on his dairy farm. His soil is a level, Verndale sandy loam. Along with the corn and beans, He considers his manure and alfalfa to be part of a long-term soil building program to increase the rooting depth of his corn. He stockpiles his manure with oat straw and hauls when the rotation allows. He was very interested at the outset to refine his knowledge of the nitrogen in his manure.

Marvin typically applies 105 lbs. of nitrogen as a sidedress to his second year corn and wanted to match this nitrogen rate with his manure application. A laboratory analysis of a combined subsample from the three month old pile revealed the following nutrient content:

Runyan Dairy Manure with Bedding	Nutrient Content
Nitrogen (organic)	0.33 %
Nitrogen (ammonia)	0.38 %
Phosphorous (P2O5)	0.12 %
Potassium (K2O)	0.54 %

We assumed that 30 % of the organic nitrogen and 100% of the ammonia would be available to the crop in the first year according to U of M recommendations. We followed the sample calculation below.

To determine available #N/ton manure:

7.6 lbN/ton (all the ammonia) + 2.0 lbN/ton (30 % of organic)= 9.6 lbN/ton available N

To achieve 105# N/acre:

(105# N /acre)/(9.6# N/ton manure) = 11 ton manure/acre

The spreader was calibrated by driving over a plastic tarp of known surface area and weighing the tarp. This was done several times until uniform results were obtained. It appeared that a fairly uniform spread was achieved.

Results

The process of testing the nutrients in the manure and calibrating the spreader allowed Marvin to cut his manure application rate in half. Even at this lower rate, it appears that he was able to provide his corn with a similar ammount of nitrogen from both the manure and the 105 lb. nitrogen as anhydrous ammonia (table F.1.1). There was a minimal overall nitrogen resoponse with the control yielding only 10 bushels under that of the manured and sidedressed treatments. The high levels of nitrate in the spring soil sample (table F.1.2) suggest a large carryover from the poor growing season in 1993. The two foot nitrate test does not officially apply to Marvin's farm due to his coarse textured soil and rainfall/ET ratio but the excellent growing conditions in 1994 may have allowed him to take credit for stored nitrate. The good yields in the manured plots were achieved without increasing the residual soil nitrate in the fall (table F.1.3).

Myron Quaal Manure Rate on Corn Demonstration

The Quaal farm is a conventional dairy with corn, wheat and alfalfa hay. He is located on a loamy sand in a region that often does not have enough warm weather to produce mature corn so Myron plans on putting up high moisture corn every year. He does not generally raise corn for sale. This is important because his attitude toward corn production is one of producing enough for the dairy. He avoids off farm inputs because he does not expect a direct return from the corn crop until he cycles it through his animals.

Myron has a liquid pit manure system. After agitation, we immediately sent a sample to the lab and obtained an analysis in 24 hours. The test showed 23.3 lb N/1000 gallons as ammonia and 15.8 lb N/1000 gallons as organic. Using the same assumption of nitrogen availability as described in the Runyan demonstration, we applied 3,700 gallons/acre to supply 105 lb N fertilizer equivalent. The spreader was calibrated by measuring the number of acres covered by a spreader of known volume.

The Quaal demonstration took an interesting turn in June and early July. Excellent growing conditions were followed by a slight drought. The rapid corn growth in mid-June caused Myron to miss the window for sidedressing nitrogen on the test plots (as well as on many of his corn acres). So the intended high nitrogen treatment wound up the same as the no nitrogen control. Although the integrity of the treatments was disrupted, the aborted sidedress was reflective of what was occurring on Moron's corn ground in general. In this sense, the lack of nitrogen in the conventional treatment was the same as he was experiencing on much of the farm.

Results

All yields were low due to lack of moisture but there was ample evidence that the manure was a dependable source of nitrogen, reflected in yield, grain protein and ear leaf nitrogen (Table F.1.4).

Soil nitrate levels were higher in the manured plots in the spring and the fall suggesting that the corn was unable to use some of the available manure nitrogen (table F.1.5 and table F.1.6).

Tobkin Manure Rate on Edible Bean Demonstration

Ron, Rick and Neal Tobkin have a large edible bean farm in Perham. They were interested in achieving agronomic rates of nitrogen in their beans with liquid hog manure. The Tobkins normally sidedress their beans with 90 lb of N as urea. They feel that the manure not only helps provide nutrition to the crop but also helps increase soil microbial activity which they feel has been on the decline in their corn, edible bean, potato rotation. They have been expanding their use of manure and alfalfa to improve their soil's long-term productive potential.

The manure was tested and the spreader calibrated using the assumptions outlined in the Runyan and Quaal demonstrations above. 18.5 lb N/1000 gal was estimated to be available so we applied 5000 gallons/acre to achieve a 90 lb N as urea equivalent.

Results

The manured beans yielded similar to the conventional treatment and higher than the control (Table F.1.7). It appears that the manure supplied sufficient nitrogen without increasing the potential for leaching. Both spring and fall soil nitrate were lower in the manured plots than in the urea plots at all three depths measured (table F.1.8 and table F.1.9).

The most interesting aspect of this demonstration was the improved root development in the manured beans. This was observed as the plants were being pulled for a harvest subsample, In an attempt to quantify this observation, root samples were saved and measured on a grid. The difference in root length is presented in table F.1.7. The manured beans had a dramatically greater root length than both the control and the urea treatments. The urea treatment had few intact tap roots and a profusion of shallow adventitious roots. This bore out the Tobkin's hunch that the beans were affecting more than just plant nutrition. In an attempt to better understand the effect of the manure on edible bean roots, a repeat of this demonstration plot has been initiated in the spring of 1995 (the Tobkins have undertaken this at their own expense). This summer, there will be a more intensive sampling of edible bean roots and root diseases.

John Moyer Potato Nitrogen Rate Demonstration

John raises 300 acres of potatoes in a potato, corn, edible bean rotation in the Verndale, Staples area. John has been refining his nitrogen sidedress splits and was interested in comparing his rates (50-80-90) to those of Dr. Carl Rosen at the U of M (25-80-115 or 25-65-70 +25 if needed, as determined by petiole nitrates). The success of the splits was assessed by yield quantity and quality and soil water nitrate levels through the season.

Results

The refined nitrogen split applications improved marketable yields and reduced the potential for leaching when compared to John Moyers conventional rates.. Reducing nitrogen rates at planting from 50 to 25 lbs/acre and making up for the deficit in the last sidedress increased marketable yields (table F.1.10). The 25-80-115 and the sap test treatments not only had the highest yields, they also had the largest number of large, well shaped tubers. It appears that the use of the petiole sap nitrate test with it's reduction from 80 to 65 lb N/acre in the second split and the delayed final 25 lb, reduced the potential for leaching (table F.1.12).
The effects of the refined splits on soil water nitrate were mixed. Nitrate levels were elevated in the 25-80-115 split from 7/14 to 7/22 and in the 50-80-90 split from 8/8 to 9/16 (table F.1.12). This may be a reflection of field spatial variability and preferential water flow rather than treatment differences. Soil nitrate levels were low in all treatments and all depths measured from 0-3 feet (F.1.13). High late sidedress treatments had slightly elevated nitrate levels.

John Moyer Deep Tillage and Nitrogen Source Demonstration

John has been concerned that his subsoil is becoming compacted enough to restrict root development. This study looked at whether deep tillage to 2 feet would break up the root restricting layer without increasing leaching potential. John was also interested in looking at the effect of 28% nitrogen vs. anhydrous ammonia on corn yield and leaching potential. Two tillage by N source demonstrations were set up, one in 1992 and one in 1993.

Results

Corn yields were not affected appreciably in 1993 by tillage or N source with the exception of low yields in the paraplow (92) with 28% treatment (table F.1.14). This trend was not apparent in the adjacent plots deep tilled in 1993 (table F.1.15). The reason for the low yields in the urea treatment is unclear.

Soil water nitrate levels were consistently higher through the growing season in the moldboard/anhydrous treatment compared to all others (Figure F.1.1). Conventional wisdom has it that anhydrous ammonia is less susceptible to leaching than 28% nitrogen. We also expected the deep tillage to increase the potential for leaching by increasing deep percolation. The yield data do not suggest a lower nitrogen use efficiency in the moldboard/anhydrous treatment so the elevated nitrate levels remain unexplained.

The border of the demonstration was damaged by herbicide in June of 1993. An interesting effect of the loss of the transpiration stream in the damaged plots can be seen in a dramatic increase in soil water nitrate (figure F.1.2). This unplanned effect points out the contribution of a healthy growing crop to reducing leaching potential.

Edible beans were raised on the deep tillage site in 1994. Bean root morphology was observed by excavating a 3' profile in mid-July. Bean roots in the deep tilled plot were common between 14" and 20". Beans in the conventionally plowed plot had few deep roots.

It appears that the deep tillage has provided a better root environment but the effect on leaching potential remains an open question.

Summary

These demonstrations provided good local examples of refined manure and nitrogen fertilizer management practices. There was strong interest in these farm communities to use this information to save money on fertilizer where manure is already being spread. The demonstrations showed that manure can be a dependable, environmentally sound sole source of nitrogen when combined with lab analysis and spreader calibration. Judging from the manure rate reductions common to all the farmers we worked with, there remains a strong need for continued farmer education on manure fertility. The potato growers are rapidly adopting the refined nitrogen sidedress splits to move toward a more dynamic match with crop needs. The use of deep tillage on coarse textured soils with a Bt horizon shows promise for deeper root development but needs to be assessed further for its effect on nitrate leaching.

Table F.1.1. Runyan Manure Rate Study Yield '94.

Treatment	yield (bu/a)	grain moisture (%)	test wt	grain protein (%)	ear leaf N(%)	basal stalk N(%)
	------- mean of three replications -------					
No N (control)	124	18.1	55.3	9.8	3.0	0.57
1/2 rate manure	136	17.5	55.6	9.9	2.9	0.53
Full rate manure	133	17.8	55.7	9.9	3.1	0.51
Anhydrous	133	17.1	55.8	9.9	3.2	0.58
Pr>F	0.512	0.767	0.764	0.838	0.335	0.108

Table F.1.2. Runyan Soil Mineral N (5-6-94).

	-- NO3 (ppm) --		NH4 (ppm)
Treatment	0-6"	6-24"	0-6"
	---- mean of three replications ----		
No N (control)	6.4	17.3	8.2
1/2 rate manure	6.6	23.0	5.7
Full rate manure	9.5	19.0	9.5
Anhydrous	7.9	25.6	5.4
Pr>F	0.127	0.723	0.033

Table F.1.3. Runyan Soil Nitrate (11-21-94).

	------- NO3 (ppm) ------		
Treatment	0-6"	6-12"	12-24"
	--- mean of three replications ---		
No N (control)	4.4	2.3	2.7
1/2 rate manure	3.2	2.0	3.2
Full rate manure	3.7	1.9	1.9
Anhydrous	9.5	8.2	5.4
Pr>F	0.001	0.001	0.002

Table F.1.4. Quaal Manure Rate Study Yield '94.

Treatment	yield (bu/a)	test wt	grain protein (%)	ear leaf N(%)
	------- mean of three replications -------			
No N (control)	66	52.4	8.1	2.2
1/2 rate manure	77	52.8	10.0	2.8
Full rate manure	90	54.8	10.0	2.6
Anhydrous (was not applied)	74	55.3	7.8	2.0
Pr>F	0.524	0.006	0.054	0.114

Table F.1.5. Quaal Soil Mineral N (5-11-94).

	-- NO3 (ppm) --		NH4 (ppm)
Treatment	0-6"	6-24"	0-6"
	---- mean of three replications ----		
No N (control)	6.2	3.2	6.5
1/2 rate manure	8.8	4.6	5.8
Full rate manure	4.4	3.6	7.0
Anhydrous (was not applied)	3.0	2.5	7.0
Pr>F	0.061	0.167	0.736

Table F.1.6. Quaal Soil Nitrate (11-21-94).

	------- NO3 (ppm) ------		
Treatment	0-6"	6-12"	12-24"
	--- mean of three replications ---		
No N (control)	1.3	3.4	1.7
1/2 rate manure	1.9	3.9	1.8
Full rate manure	3.7	6.6	5.6
Anhydrous	1.8	3.1	1.4
Pr>F	0.021	0.196	0.113

Table F.1.7. Tobkin Manure Rate Study Yield '94.

Treatment	yield (lb/a)	root length (in)
	- mean of three replications -	
No N (control)	1507	30
1/2 rate manure	2528	90
Full rate manure	2493	75
90 lb N as Urea	2349	53
Pr>F	0.059	0.001

Table F.1.8. Tobkin Soil Mineral N (5-6-94).

	-- NO3 (ppm) --			NH4 (ppm)
Treatment	0-6"	6-12"	12-24"	0-6"
	---- mean of three replications ----			
No N (control)	8.5	9.3	10.1	5.6
1/2 rate manure	8.6	7.0	7.6	6.3
Full rate manure	13.6	11.8	8.2	6.6
90 lb N as Urea	8.4	13.0	10.0	4.2
Pr>F	0.632	0.437	0.704	0.714

Table F.1.9. Tobkin Soil Nitrate (10-2-94).

	-- NO3 (ppm) --		
Treatment	0-6"	6-12"	12-24"
	- mean of three replications -		
No N (control)	4.1	3.5	3.1
1/2 rate manure	5.4	3.8	3.4
Full rate manure	5.0	3.3	3.2
90 lb N as Urea	9.0	5.6	5.4
Pr>F	0.168	0.146	0.027

Table F.1.10. Moyer Potato N Rate Study Yield '94.

Treatment	0-3 oz.	3-6 oz.	6-12 oz.	>12 oz.	total>3oz.	knobs
		------- tuber size		-------		
	------- mean of four replications (lb/acre)				-------	
50-80-90	4345	9664	20323	3596	33583	1466
25-80-115	3264	12147	21821	4944	38913	760
25-65-70 (+25?)*	4677	13313	21222	4409	38945	1627
25-65-70	4292	12200	19735	2708	34643	1006
Moyer field	3874	13131	20730	1466	35327	1595
Pr>F	0.004	0.392	0.047	0.327	0.115	0.023

* 25 lb N added as needed by sap test (was added on 6/30)

Table F.1.11. Moyer Soil Mineral N (6-10-94).

Treatment	0-6"	0-12"	12-24"	24-36"	0-6"
	-- NO3 (ppm) --				NH4 (ppm)
	---- mean of three replications ----				
50-80-90	13.1	7.9	2.9	2.0	24.1
25-80-115	12.2	7.6	2.6	1.9	38.9
25-65-70 (+25?)*	14.2	6.7	2.8	1.9	29.0
Pr>F	0.924	0.507	0.882	0.965	0.487

* 25 lb N added as needed by sap test (was added on 6/30)

F.1.12. Moyer Potato Study Soil Water Nitrate '94

Treatment	6/17	6/20	6/23	6/30	7/8	7/14
			----- Date -----			
		------- NO3 (ppm) -------				
50-80-90	14.7	7.9	9.7	12.5	12.0	29.5
25-80-115	24.0	2.4	21.5	23.0	28.9	59.0
25-65-70 (+25?)*	14.3	1.2	8.4	12.1	20.2	26.6
25-65-70	21.6	23.4	28.3	41.4	28.5	41.3
	7/22	7/22	7/29	8/8	8/19	9/16
50-80-90	32.7	32.7	39.0	37.5	38.9	28.9
25-80-115	59.2	59.2	36.9	23.3	13.5	13.9
25-65-70 (+25?)*	23.2	23.2	16.1	12.5	9.1	8.1
25-65-70	41.4	41.4	27.6	13.5	6.9	11.2

* 25 lb N added as needed by sap test (was added on 6/30)

Table F.1.13. Moyer Soil Nitrate (11-18-94).

Treatment	0-12"	12-24"	24-36"
	-- NO3 (ppm) --		
	- mean of three replications -		
50-80-90	2.1	1.2	0.8
25-80-115	1.9	1.7	1.7
25-65-70 (+25?)*	2.2	2.9	1.6
25-65-70	1.3	1.2	0.8
Pr>F	0.009	0.002	0.024

* 25 lb N added as needed by sap test (was added on 6/30)

Table F.1.14. Moyer Tillage (92) by N Source Study Yield '93.

	Treatment	yield (bu/a)	grain N (%)	basal stalk N(%)
		--- mean of three replications ---		
92 Moldboard	Anhydrous	69	1.6	0.57
	28%	69	1.7	0.52
92 Paraplow	Anhydrous	71	1.6	0.58
	28%	54	1.7	0.62
	Pr>F	0.001	0.274	0.598

Table F.1.15. Moyer Tillage (93) by N Source Study Yield '93.

	Treatment	yield (bu/a)	grain N (%)	basal stalk N(%)
		--- mean of three replications ---		
93 Moldboard	Anhydrous	76	1.6	0.54
	28%	66	1.6	0.59
93 Paraplow	Anhydrous	67	1.6	0.62
	28%	68	1.6	0.60
	Pr>F	0.858	0.962	0.299

Table F.1.16. Moyer Soil Mineral N (Fall 93).

	Treatment	NO3 (ppm) 0-2'	NO3 (ppm) 0-2'
		92 till	93 till
Moldboard	Anhydrous	4.4	5.8
	28%	3.8	7.0
Paraplow	Anhydrous	4.9	6.8
	28%	3.9	7.4
	Pr>F	0.151	0.602

Table F.1.17. Moyer Edible Bean Yield (94).

Treatment	Yield lb/acre
Moldboard	3441
Paraplow	3397
Pr>F	0.632

Figure F.1.1. Effect of Tillage and N Source on Soil Water NO3

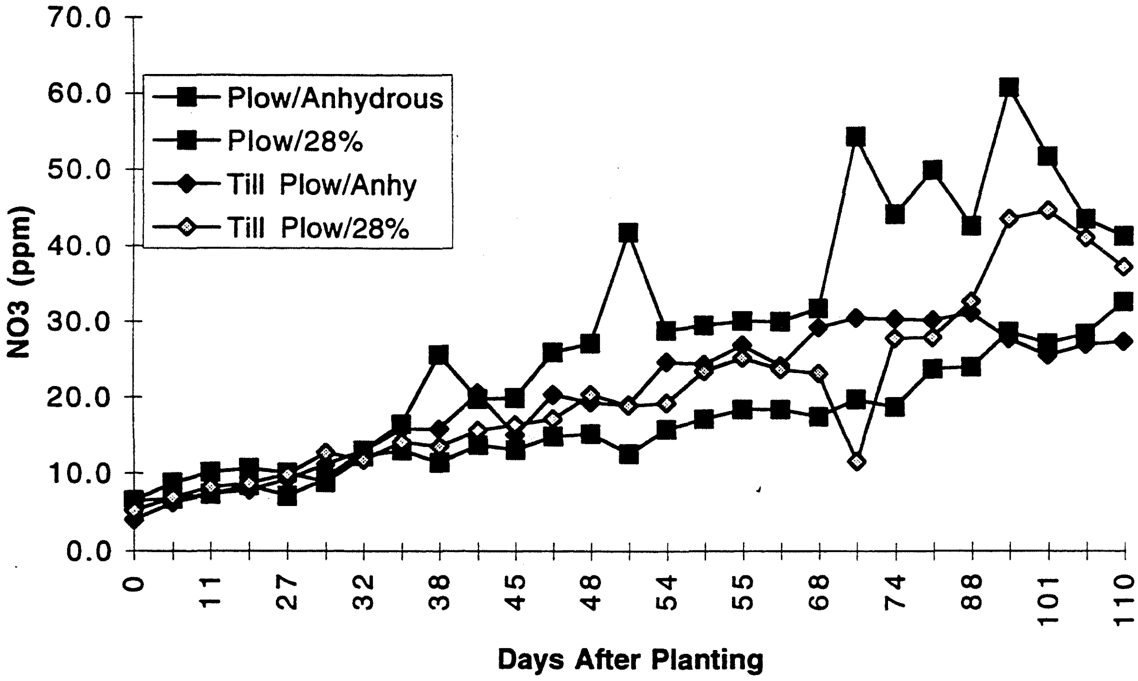
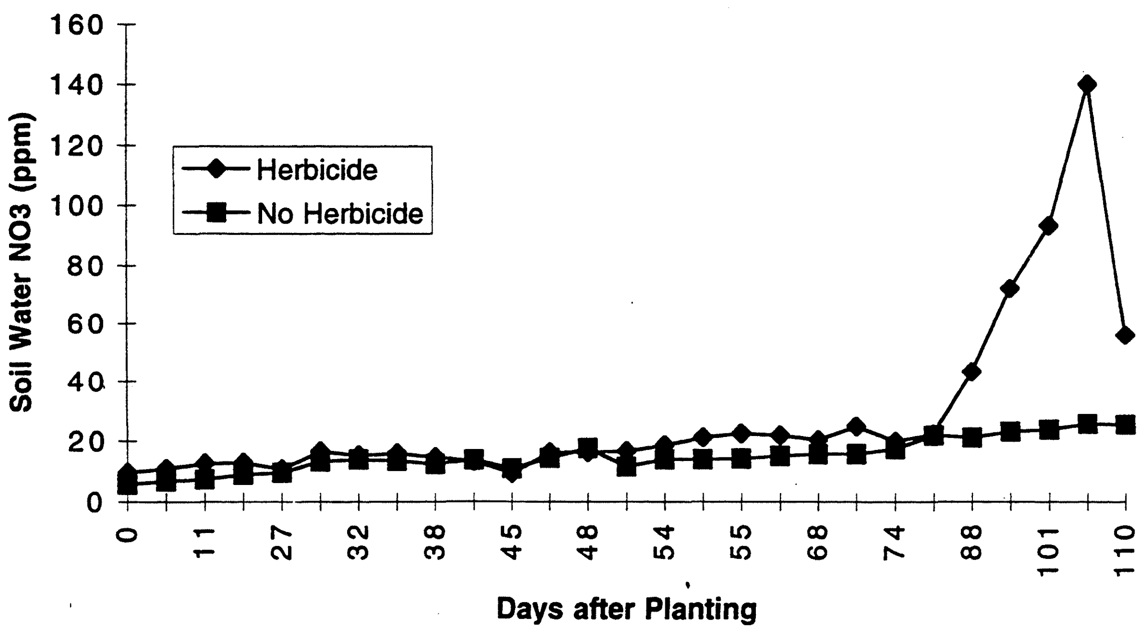


Figure F.1.2 Effect of Herbicide Damaged Corn on Soil Nitrate



F.2. Activity: Produce demonstration data summaries and conduct workshops for farmers and field staff of local agencies .

F.2.a. Context within the project: Information from the on-farm demonstrations and other project objectives have been summarized to allow growers to compare how their practices affect nitrate movement and production and to encourage adoption of new guidelines that will decrease losses of nitrate nitrogen while maintaining profitable farming operations.. The impact of this information has been increased because the data came directly from local farmers' fields. Joint training of field staff of the Minnesota Extension Service, the Soil Conservation Service, and Soil and Water Conservation Districts will greatly multiply the information dissemination efforts by using "in place" agency field staff as vehicles for information transfer.

F.2.b. Methods: All cooperating farmers met to evaluate the data collected. Farmers and field staff are meeting again in mid-July to determine the program for farmer and field staff workshops. Decisions on number and location of the programs will be made at that time. Presentations from both farmer cooperators and researchers will be included. Data from the demonstrations and other research components will be summarized into workshop presentation materials and fact sheets for general distribution in the North-Central Sands area.

F.2.c. Materials: Data collected during the 2 years of the project as well as information obtained from previous projects and complementary projects will be integrated to produce the fact sheets and workshop presentation materials.

F.2.d. Budget: $10,000.
Remaining: $0.00.

F.2.e. Timeline:

	7/93	1/94	6/94	1/95	6/95
Prepare data summaries and fact sheets		****	****	****	****
Field staff training workshops			****		****
Farmer training workshops			****		****

F.2.f. Status: Data summaries have been reviewed with all farmer-cooperators. A meeting of farmer-cooperators, U of M Extension and NRCS staff is scheduled for mid-July to incorporate the results into fact sheets as well as to continue the manure dialogue begun on April 13. Through these demonstrations, farmers have shown their understanding of the complexity of the manure issue. The manure discussion has expanded from plant nutrition to include soil quality/health. Below is a summary of the April 13, 1995 meeting between Perham area farmers and support staff.

Perham Soil Quality Meeting

The following is a synthesis of a discussion on soil quality that occurred on April 13, 1995 with Perham area farmers and support staff. These are the combined comments of three farmers and one representative of each of the following: the NRCS, U of M Extension Service and a USDA ARS researcher. The meeting was borne out of concern by local edible bean growers that soil health is declining. All participants were asked in advance to think about the following questions:

- How do you describe a healthy soil?
- Have you seen changes in soil quality/health on your and neighboring farms (both across the landscape and over time). Can you give examples of how these changes relate to specific farming practices?
- In the future, can farm management be geared to long-term soil health to improve overall production and increase profitability in an environmentally sound way? How do we accomplish this?

Meeting Notes

Overall Perspective: The general concern is that loss of soil quality has resulted in lower productivity and greater erosion (particularly wind erosion). Loss of soil quality is closely related to the loss of organic matter due to the narrowing of rotations. Older animal-based farms were more diversified (manure, legumes and grasses) but there have been changes in societal values, making it unlikely that young farmers would put up with twelve hour days and the low return associated with the small dairy.

The present farm economy drives farmers away from building soil quality. Low profit margins on grain force the farmer to focus on volume which translates into more acres in grain. This has been facilitated by the improvement of weed control technology, prior to which the farmer was forced to keep more land in cover (hay and pasture). Now, there is no market for alfalfa.

The corn-edible bean-potato rotation has become popular in the Perham area due to the high value of edible beans and potatoes but these two crops return less residue to the soil than any other crops. We have achieved efficiency at the expense of soil health but this change has occurred slowly over an extended period of time. It is important to remember that we are not just talking about soil health here. Everything is connected. Soil health is the key to the health of Main Street in Perham.

How Do You Observe Soil Health? A healthy soil is more productive. Manured soil yields beyond the N-P-K value of the manure. We're getting a crop response to the organic matter in the manure. Dairy ground is producing better beans than row crop ground.

Good soil has better tilth. It is more fluffy, soft and loose. Poor soil is limp and hard with big clods that are hard to break up. You can feel the difference by how the tractor bounces over the ground: healthy soil is spongy and bounces back, poor soil is hard. In good soil, the tire tracks sink in more and hold their shape. In poor soil, the tread marks fall apart. There used to be worms, but we're not finding worms anymore.

Poor soil can't hold water so we need to irrigate more often.

Chemical carryover is worse in depleted soils. The windblown ridges have more chemical carryover than the valleys. The valleys have more microbial activity to help break down the chemicals.

Wind erosion is worse on poor soil. You can see increased wind erosion on farms with only a potato-grain rotation compared to a dairy.

You could really see the good soil quality when you plowed up the soil bank thirty years ago. It was black, deep, loose topsoil and was very easy to work.

How Might Soil Quality Be Measured? Possible measures might include: bulk density, C.E.C., tensiometer, water holding capacity, nutrient availability and, most importantly, organic matter and yield.

What Can We Do? Generally, we already know how to tell a good quality soil by working it and we know how to improve soil quality by using manure, grasses and legumes. But we need ways to use these tools within the current structure of agriculture. The big key is animals. We need more animals in the county but we continue to lose our dairy farmers. Animals create manure, alfalfa, nitrogen and prevent erosion. We need to document the positive value animals have on the environment so that environmentalists understand their value as well.

We need to look at potential markets for alfalfa. There is potential in the Granite Falls pilot energy project. Is there room for expanding the use of alfalfa in Perham industry?

We need to look again at the effect of manure on the health of edible bean roots.

There are some sources of manure and other organic materials that are presently undependable soil amendments due to the presence of pathogens and weed seeds. If they are to become useful, farmers need to know that the high value crops are not put in jeopardy. Two examples are: weed seeds in poultry manure and carryover of sclerotia in sunflower hulls.

Green manure crops need to be improved. They need to be fast growing for our short season.

No-till has problems in beans. It increases disease carryover in edible beans and prevents warming of the soil in spring.

We need to broaden the perspective of the soil quality problem. We need to keep in mind the relationship of soil health to the whole farm and the community. We also need to plan for the long-term. The productivity of our high value crops depends on soil health.

V. Evaluation: Each individual objective will be evaluated on how well each achieved specific research and educational goals. Evaluation of the overall project will be obtained by feed back from field staff as to the amount of changes in farmer practices which could affect the extent of contamination of ground water by agricultural chemicals.

VI. Context within Field: Quantitative field measurement of nitrate and herbicide movement through soil is very expensive and difficult. For this reason there is paucity of data in this area of research. This project will provide critical data dealing with agricultural chemical use on irrigated sandy soils overlaying surficial aquifers. The computer modeling component will provide an opportunity for interpolation to many soil\climate circumstances which will have application over parts of four states in the upper Midwest.

VII. Benefits: The most valuable benefit to Minnesota is the potential reduction of agricultural chemicals from loss to groundwater.

VIII. Dissemination: This project has an objective devoted entirely to technology transfer and information dissemination. In place field based staff of the Minnesota Extension Service, the Soil Conservation Service, Soil and Water Conservation Districts, and the Minnesota Department of Agriculture will be responsible for information dissemination with participation from state based staff.

IX. Time: This information generated from this project will be limited by its one biennium time frame but nevertheless should yield useful data.

X. Cooperation: Cooperators will include eight faculty at the University of Minnesota, five specialists at the Minnesota Department of Agriculture, six county Extension agents, the Staples Area Technical College Irrigation Center, R.D. Offutt Co., and the Irrigators Association of Minnesota.
The activities under this project will be coordinated with those under several on-going projects of similar nature. However, this project has several unique variables not addressed by other projects. There have been very few previous research efforts in Minnesota related to nitrogen fate and movement in soil under potato production. Other states such as Wisconsin have conducted nitrogen-related research on irrigated potatoes and these results have been used to help formulate the treatments proposed in the present project. Two other projects are also being conducted in the sand plains area. Several Soil Science faculty members are participating in these projects. The Anoka Sand Plain demonstration project is based on current knowledge of best management practices, not on potential improvements of these practices. For a high value crop such as potato, untested changes in production could lead to substantial monetary losses. Therefore, changes in nitrogen management practices have to be studied on a small scale before they can be recommended to growers. The Management Systems Evaluation Area (MSEA) project has been set up to quantify losses of nitrate in a defined system, with emphasis on fertilizer use and corn production, but does not address nitrogen management practices or diagnostic techniques to help reduce these losses. Coordination with the Pineland Clean Water Partnership Project conducted in the Park Rapids area will also be undertaken. Preliminary discussions with Pineland project leaders including cooperating scientists from the U.S. Geological Survey have already been completed. The demonstration component will be incorporated into several existing programs: the Anoka Sand Plains Project, the SCS-Extension Nutrient Management/Conservation Tillage Program, and the Pineland Clean Water Project.

Note: Those cooperators listed that do not have a time commitment are being used as consultants only and will not be responsible for status reports.

A. **Dr. H.H. Cheng**, Soil Chemist, Soil Science Department, UM, will be the principal investigator on the herbicide leaching evaluation. Two year time commitment - 10%. Dr. Cheng is project manager for the two year duration - 5% time; He will also coordinate activities described in Objective D over the two year duration of the project - 5% time.
B. **Dr. Satish C. Gupta**, Soil Physicist, Soil Science Department, UM, will provide leadership in the water flow modeling and field validation effort. Two year time commitment - 5%. Dr. Gupta will contribute to Objective E1 and E2 over the two year duration of the project - 5% time.
C. **Dr. Jean A.E. Molina**, Soil Microbiologist, Soil Science Department, UM, will provide advice on the N transformation dimension of several objectives and have primary responsibility for the computer modeling efforts. Two year time commitment - 5%. Dr. Molina will contribute to objective E4 over the two year duration of the project - 5% time.
D. **Dr. John F. Moncrief**, Extension Soil Scientist, Soil Science Department, UM, will advise on the field demonstrations and provide leadership in the corn-N source evaluation. Two year time commitment - 5%. Dr. Moncrief will contribute to Objective C2 over the two year duration of the project - 5% time.
E. **Dr. Clive F. Reece**, Soil Atmospheric Physicist, Soil Science Department, UM, will provide leadership in the water flow modeling and field validation effort addressing stem and canopy flow of water and contaminants. Two year time commitment - 10%. Dr. Reece will contribute to objective C1 during the two year duration of the project - 10% time.
F. **Dr. Carl J. Rosen**, Extension Soil Scientist, Soil Science Department, UM, will advise on the field demonstrations and provide leadership in the potato-N management phase. Two year time commitment - 12.5%. Dr. Rosen will contribute to the coordination of Objectives B (5% time) and C1 (5% time) and will assist in supervising field operations in objective D (2.5% time) over the two year duration of the project.
G. **Dr. Mark W. Seeley**, Extension Climatologist, Soil Science Department, UM, will provide leadership on the climatic influences on conditional probabilities for field working days and leaching losses of contaminants. Two year time commitment - 6%. Dr. Seeley will contribute to objectives E2 (2% time) and E3 (4% time) over the two year duration of this project.
H. **Mr. Jerry A. Wright**, Extension Agricultural Engineer, will provide expertise on the irrigation scheduling dimension of the modeling and field validation efforts.
I. **Mr. Bruce R. Montgomery**, Special Projects Coordinator, Minnesota Department of Agriculture, will have primary responsibility for the farming practices

survey. Two year time commitment - 4%. Mr. Montgomery will coordinate and administer objective A over the two year duration of the project - 4% time.
J. **Mr. Doug J. Gunnink**, On-farm project coordinator, Minnesota Department of Agriculture, will have primary responsibility for coordination of the "farmer cooperator" demonstrations. Two year time commitment - 20% Mr. Gunnink will be responsible for coordinating the demonstration projects in Objective F over the two year duration of the project - 20% time.
K. **Dr. Mary J. Hanks**, Supervisor, Energy and Sustainable Agriculture Program, Minnesota Department of Agriculture, will have primary responsibility for supervision of the "farmer cooperator" demonstrations. Two year time commitment - 2.5% time. Dr. Hanks will contribute to review and supervision of the demonstrations described in Objective F over the two year duration of the project - 2.5% time.
L. **Mr. Norman J. Krause**, Executive Director of the Irrigators Association of Minnesota, will be providing input for potential survey respondents and farming relevance of research goals.
M. **Mr. Dale Steevens**, Agronomist, R.D. Offutt Co., will cooperate on field evaluation of irrigated potatoes for N management and irrigation scheduling research objectives.
N. **Mr. Mel Wiens**, Senior Plot Coordinator, Ag. Exp. Sta., UM will supervise treatment establishment and data collection at the Staples Irrigation Center.
O. **Ms. L. Axton, Mr. D. Cooper, Mr. T. Hovde, Mr. R. Stauffer, Mr. L. Williams, and Mr. W. Yliniemi** Minnesota Extension Service, will coordinate the educational activities in their respective counties.

XI. Reporting Requirements: Semiannual status reports will be submitted not later than Jan. 1, 1994, July 1, 1994, Jan. 1, 1995 and a final status report by June 30, 1995.

XII. Literature Review

Nitrogen Balance: Most of the studies conducted on the outwash soils of the north central United States only deal with nitrate uptake and leaching under corn production. Gerwing et al. (1978, 1979) studied the effects of amount and timing of nitrogen fertilizer applications on N uptake by irrigated corn and the movement of N into the aquifer 4.5 m below the soil surface. The soil in this study was a Sverdrup loamy sand. Nitrogen was applied as urea at rates of 179 and 269 kg/ha in one application at planting or in split applications through the season. A split application had minimal effect on the concentration of nitrate-N in the aquifer but one time application of fertilizer increased the concentration of nitrate-N in the aquifer by 7 to 10 ppm. The use of N15 showed that splitting the 179 kg/ha rate increased the N in the plant derived from fertilizer from 33.1 to 54.1%, even though whole plant yield was not affected.

Timmons and Dylla (1981) evaluated the effect of two nitrogen fertilization methods and two supplemental irrigation levels on soil water percolation and N leaching losses under corn in West Central Minnesota. Nitrogen was applied either as granular urea broadcast and disked in before planting or through irrigation as urea-ammonium nitrate solution four times during the growing season. Supplemental irrigation was applied as either a partial replenishment (2.5 cm) or full replenishment (5 cm) irrigation each time the available soil water decreased to about 5 cm (50% depletion). Annual soil water percolation from spring thaw to fall freeze-up averaged about 7.1, 11.2, and 18.0 cm for non-irrigated corn, 2.5-cm irrigated corn, and 5-cm irrigated corn, respectively, during the 5 year study. Average annual nitrate-N leaching losses ranged from about 29 (for non-fertilized, non-irrigated corn) to 112 kg/ha. Compared with values for fertilized non-irrigated corn, annual nitrate-N leaching losses increased by an average of 17 and 53%, respectively, for partial and full replenishment irrigations. The split application of N solution through the irrigation system reduced average annual nitrate-N leaching loss by about 12 kg/ha at the 5 cm irrigation level, but no difference was observed at the 2.5-cm level.

Montgomery et al. (1990) studied the effects of two irrigation management schemes (fixed 40% depletion vs. variable depletion based on crop phenology) and two nitrogen rates (95 vs. 145 kg ha-1 yr-1) on nitrate leaching in drainage lysimeters under corn in North Dakota. Drainage accounted for 29% of the total water input. Spring recharge accounted for 60% of the yearly drainage and nitrate leaching losses. Drainage and nitrate leaching losses during the active irrigation season were approximately 25% of annual load despite large inputs of water and inorganic N into the system during this period. The most conservative scheduling (variable depletion) required 25% less irrigation water and reduced annual drainage and nitrate-N leaching by 15 and 30%, respectively.

The most detailed study of N uptake and leaching under potato production in north central United States is the study by Saffinga et al. (1976, 1977a, b) on Plainfield loamy sand in central Wisconsin. These authors reported that carefully managed "improved" treatment (170 kg/ha nitrogen in 10 applications and 27 cm irrigation) compared to the "conventional" treatment (260 kg/ha in four applications and 45 cm irrigation as 2.5 cm every 5 days) decreased nitrate-N leaching from 200 to 120 kg N/ha. The overall average nitrate-N concentration of the leachate decreased from 23 to 6 ppm. Total yields were the same for conventional and improved treatments for both years. In one year, the yield of grade A tubers was even higher under the improved treatment compared to conventional treatment despite a decrease in fertilizer and N application. Studies are needed to identify the splits in nitrogen application at optimal irrigation that will minimize nitrate leaching but will produce the maximum potato yield.

Herbicide movement: Few studies have been conducted on herbicide fate in soils under field conditions for irrigated potato production. Only recently, Burgard et al. (1992) completed a two year study on the movement of metribuzin in an irrigated potato field at Becker, MN. Since climatic regimes, cultural practices, rooting patterns, fertilizer placement, and irrigation schemes for potato production are different from those for other crops, the fate and transport of herbicides in irrigated potato fields could also be different. The Burgard study will serve as a guide for designing relevant studies for this project.

Modeling: Numerous efforts (Iritani, 1963; Manrique and Bartholomew, 1991, Ng and Loomis, 1984; Ingram and McCloud, 1984 and Ritchie et al., 1991) have been made to model the growth and development of potato. These models vary widely in complexity and objectives. The SUBSTOR model of Ritchie et al. (1991) not only considers the growth and development of potato but also includes a submodel of water and nitrate movement in soil. The basic structure of SUBSTOR is similar to the family of CERES models (Jones et al., 1986) that have been extensively tested over a wide range of soil and climatic conditions. The SUBSTOR model was recently put together, and has not been extensively tested. Furthermore, the model is a one-dimensional model and thus does not include the effects of hilling on water and NO3 movement.

Recent testing of SUBSTOR and CERES-Maize by the authors of this proposal (Perillo et al., 1993; Pang et al., 1993) have shown that improvements are needed in CERES models like SUBSTOR to account for spatial placement of nitrogen in the potato hill, and differential water flow due to canopy dripping and stem flow. More specifically, to adopt SUBSTOR to conditions of non-uniform application of water, the model needs to be modified to account for two dimensional water and nitrate distribution.

There exists a number of models describing the fate and transport of pesticides in the soil environment (Wagenet and Rao, 1990). Most of the process models were developed from laboratory generated data; few have been tested under field conditions or in the presence of a crop. This project intends to test the applicability of Wagenet's LEACHM model to describe herbicide movement under the field conditions for irrigated potato production.

Literature Cited

Burgard, D.J., R.H. Dowdy, W.C. Koskinen, and H.H. Cheng. 1992. Movement of metribuzin in a sandy soil under irrigated potato production. Soil Tillage Res. (in press).

Gerwing, J. R. 1978. Water quality of aquifers as affected by movement of fertilizer nutrients under irrigation. M. S. Thesis, University of Minnesota, St. Paul, MN, p83.

Gerwing, J. R., A. C. Caldwell, and L. L. Goodroad. 1979. Fertilizer nitrogen distribution under irrigation between soil, plant and aquifer. J. Environ. Qual., 8: 281-284.

Ingram, K. T. and D. E. McCloud. 1984. Simulation of potato crop growth and development. Crop Sci. 24: 21-27.

Iritani, W. M. 1963. The effect of summer temperature in Idaho on yield of Russett Burbank potatoes. Amer. Potato J. 40:47-52.

Manrique, L. A. and D. P. Bartholomew. 1991. Growth and yield performance of potato growth at three elevations in Hawaii. II. dry matter production and efficiency of partitioning. Crop Sci. 31: 367-372.

Montgomery, B.R., L. Prunty, and E.C. Stegman. 1990. Influence of irrigation and nitrogen management on nitrate leaching losses. pp. 28-37. In: Proc. of the North Dakota Water Quality Symposium, Bismark, ND. March 20-21, 1990. North Dakota State University Extension Service, Fargo, ND.

Ng, E. and R. S. Loomis. 1984. Simulation of growth and yield of the potato crop. Simulation Monograph Pudoc, Wageningen.

Pang, X, S. C. Gupta, J. F. Moncrief, C. J. Rosen, and H. H. Cheng. 1993. Assessment of Minnesota Glacial Outwash soils to nitrate leaching. II. Validation of the CERES-Maize computer model to predict corn yield and nitrate leaching. To be presented at the Soil and Water Conservation Society Conference "Agricultural research to Protect Water Quality" at Minneapolis, Mn during Feb. 21-24, 1993.

Perillo, C., S. C. Gupta, C. J. Rosen, J. F. Moncrief and H. H. Cheng. 1993. Assessment of Minnesota Glacial Outwash oils to nitrate leaching. III. Validation of the SUBSTOR computer model to predict potato yield and nitrate leaching. To be presented at the Soil and Water Conservation Society Conference "Agricultural research to Protect Water Quality" at Minneapolis, Mn during Feb. 21-24, 1993.

Ritchie, J. T., B. S. Johnson, and T. Hodges. 1991. SUBSTOR-A functional model of potato growth, development and yield. Presented at the proceedings of the workshop on GCTE (Global Change and Terrestrial Ecosystems) core project of IGBP (International Geosphere Biosphere Program), The Netherlands, Sept., 1991.

Saffinga, P. G., C. B. Tanner and D. R. Keeney. 1976. Non-uniform infiltration under potato canopies caused by interception, stemflow and hilling. Agron. J., 68: 337-342.

Saffinga, P. G., D. R. Keeney and C. B. Tanner. 1977a. Nitrogen, chloride and water balance with irrigated Russet Burbank potatoes in a sandy soil. Agron. J. 69: 251-257.

Saffinga, P. G. and D. R. Keeney. 1977b. Nitrogen and chloride uptake by irrigated Russet Burbank potatoes. Agron. J. 69: 258-264.

Simunek, J; T. Vogel, and M. Th. van Genuchten. 1992. The SWMS-2D code for simulating water flow and solute transport in two-dimensional variably saturated media. Version 1.1. USDA-ARS, U. S. Salinity laboratory, Research Report No. 126, p169.

Timmons, D. R. and A. S. Dylla. 1981. Nitrogen leaching as influenced by nitrogen management and supplemental irrigation level. J. Environ. Qual.,10: 421-426.

Wagenet, R.J. and P.S.C. Rao. 1990. Modeling pesticide fate in soils. p.

351-399. IN H.H. Cheng, ed. Pesticides in the soil environment: Processes, impacts, and modeling. SSSA Book Series No. 2. Soil Science Society of America, Inc., Madison, WI.

APPENDIX

Qualifications:

H. H. CHENG

Two year time commitment - 10%

Dr. Cheng is project manager for the two year duration - 5% time; He will also coordinate activities described in Objective D for the next two years - 5% time.

University of Minnesota
Department of Soil Science
Professor and Head

Education

Berea College, Berea, KY B.A. 1956. Agricultural Science
University of Illinois, Urbana, IL M.S. 1958. Agronomy
University of Illinois, Urbana, IL Ph.D. 1961. Soil Science

Employment History

At University of Minnesota: Professor and Head, Department of Soil Science, 1989-present

At Washington State University: Professor, Department of Agronomy and Soils, 1977-89, Interim Chair 1986-87, Associate Professor 1971-77, Assistant Professor 1965-71; Chair, Program in Environmental Science and Regional Planning, 1988-89,1977-79; Associate Dean, Graduate School, 1982-86.

At Iowa State University: Assistant Professor, Department of Agronomy, 1964-65; Research Associate 1962-64.

Professional Activities and Recognitions

Fellow, Soil Science Society of America (elected 1983); Fellow, American Society of Agronomy (elected 1983); Fellow, American Association for the Advancement of Science (elected 1990); Sigma Xi, Phi Kappa Phi, Gamma Sigma Delta; Fulbright Research Scholar, State Agricultural University, Ghent, Belgium (1963-64); Guest Scientist, Jülich Nuclear Research Center, Federal Republic of Germany, 1972-73, 1979-80; Guest Scientist, Federal Agricultural Research Center, Braunschweig, FRG (1980); Associate Editor, Journal of Environmental Quality (1983-88). Member, Boards of Directors, American Society of Agronomy and Soil Science Society of America (1990-93).

Specialization and Research Interest

Soil biochemistry and soil analytical chemistry; transformation and transport of nitrogen, pesticides, allelochemicals, and organic matter in the soil environment; development and application of ^{14}C and ^{15}N tracer methodology for soils research; residue management and soil nitrogen availability; nitrogen use efficiency and ground water quality; climatic effects on carbon and nitrogen cycling.

Recent Publications (last 5 years)

Roberts, S., and H. H. Cheng. 1988. Estimation of critical nutrient range of petiole nitrate for sprinkler-irrigated potatoes. Am. Potato J. 65:119-124.

Lehmann, R. G., and H. H. Cheng. 1988. Reactivity of phenolic acids in soil and formation of oxidation products. Soil Sci. Soc. Am. J. 52:1304-1309.

Cheng, H. H. 1989. Assessment of the fate and transport of allelochemicals in the soil. p. 209-216. In C. H. Chou and G. R. Waller, eds. Phytochemical Ecology: Allelochemicals, Mycotoxins, and Insect Pheromones and allomones. Institute of Botany, Academia Sinica Monogr. Ser. No. 9, Taipei.

Roberts, S., H. H. Cheng, and F. O. Farrow. 1989. Nitrate concentration in potato petioles from periodic applications of ^{15}N-labeled ammonium nitrate fertilizer. Agron. J. 81:271-274.

Mulla, D. J., H. H. Cheng, G. Tuxhorn, and R. Sounhein. 1989. Management of ground water contamination in Washington's Columbia Basin. State of Washington Water Research Center Reprt No. 72. 29 p.

Cheng, H. H. 1990. Organic residues in soils: Mechanisms of retention and extractability. Intern. J. Environ. Anal. Chem. 39:165-171.

Cheng, H. H. 1990. Pesticides in the soil environment: An overview. p. 1-5. In: H. H. Cheng, ed. Pesticides in the soil environment: Processes, impacts, and modeling. SSSA Book Ser. No. 2. Soil Science Society of America, Madison, WI.

Cheng, H. H., ed. 1990. Pesticides in the soil environment: Processes, impacts, and modeling. SSSA Book Ser. No. 2. Soil Science Society of America, Madison, WI. 530 p.

Cheng, H. H., and D. J. Mulla. 1990. Sample analyses for groundwater studies. p. 90-96. In: D. W. Nelson and R. H. Dowdy, ed. Methods for Ground Water Quality Studies. Proceedings of a National Workshop, Arlington, Virginia, November 1988. University of Nebraska, Lincoln.

Nor, Y. M., and H. H. Cheng. 1990. Characterisation of H^{+} and Cu^{2+} binding to humic and fulvic acids. Chem. Speciat. Bioavail. 2:93-101.

Roberts, S., H. H. Cheng, and F. O. Farrow. 1991. Potato uptake and recovery of nitrogen-15-enriched ammonium nitrate from periodic applications. Agron. J. 83:378-381.

Cheng, H. H., S. E. Swanson, and T. E. McKone. 1991. Fate and transport of dioxins and furans in soil. p. 21-28. In J. W. Gillett et al. Peer Review of "Land Application of Sludge from Pulp and Paper Mills Using Chlorine and Chlorine-Derivative Bleaching Processes: Proposed Rule" for Human Dietary and Ecotoxicological Risks. U.S. Environmental Protection Agency, Office of Toxic Substances, Washington, D.C.

Cheng, H. H. 1992. A conceptual framework for assessing allelochemicals in the soil environment. p. 21-29. In: S. J. H. Rizvi and V. Rizvi, eds. Allelopathy: Basic and Applied Aspects. Chapman & Hall, London.

Roberts, S., H. H. Cheng, and I. W. Buttler. 1992. Recovery of starter nitrogen-15 fertilizer with supplementarily applied ammonium nitrate on irrigated potato. Am. Potato J. 69:309-314.

Larson, W. E., and H. H. Cheng. 1992. Information systems for soil management. p. 131-141. In: V. W. Ruttan, ed. Sustainable Agriculture and the Environment. Westview Press, Boulder CO.

Burgard, D. J., R. H. Dowdy, W. C. Koskinen, and H. H. Cheng. 1992. Movement of metribuzin in a sandy soil under irrigated potato production. Soil Tillage Res. (in press)

DOUGLAS J. GUNNINK

Two year time commitment - 20%

Mr. Gunnink will be responsible for coordinating the demonstration projects in Objective F over the two year duration of the project - 20% time.

Department: Minnesota Department of Agriculture
Ag Planning & Development Division
Rank: Sustainable Agriculture On-Farm Research Coordinator

Education

B.S., Agricultural Education, University of Minnesota, 1975.

Employment History

1989 - present On-Farm Research Coordinator for the Energy and Sustainable Agriculture Program, Minnesota Department of Agriculture.
1987 - 1989 County Extension Agent for the Sibley County Extension Office
1984 - 1986 Adult Farm Management Instructor for Pine Technical Institute
1985 - 1986 Contractor for Farmers Home Administration
1981 - 1984 Project Manager for Rural Ventures, Inc.
1975 - 1981 Vocational Agriculture Instructor for Albany Area Schools

Professional and Honorary Societies

Director, Minnesota Dorset Association
Treasurer, Minnesota Lamb & Wool Producers
Committee for livestock certification rules, Organic Growers and Buyers

SATISH C. GUPTA

Two year time commitment - 5%
Dr. Gupta will contribute to Objective E1 and E2 over the two year duration of the project - 5% time

Professor of Soil Science
Soil Science Department, U of MN

Education:

Ph. D., Utah State University, Logan, UT
M. Sc. and B. Sc., Punjab Agricultural University, India.

Employment History:

Professor, University of Minnesota, 1988-present
Associate Professor, University of Minnesota, 1985-1988
Soil Scientist, USDA-ARS, St. Paul, MN, 1977-85
Research Fellow, University of Minnesota, St. Paul, MN, 1972-77 Research Assistant, Utah State University, Logan, UT, 1969-72.

Memberships:

Soil Science Society of America
American Society of Agronomy Society
International Soil Science Society
Soil and Tillage Research Organization
American Society of Agricultural Engineers
American Geophysical Union
American Association for Advancement of Science.

Selected Publications

Ela, S. D., S. C. Gupta, and W. J. Rawls. 1992. Macropore and surface interactions affecting water infiltration into soil. Soil Sci. Soc. Am. J., 56: March-April, (in press).

Gupta, S. C., Birl Lowery, J. F. Moncrief, and W. E. Larson. 1992. Modeling tillage effects on soil physical properties. Soil Tillage Res. 20: 293-318.

Sharma, P. P., S. C. Gupta, W. J. Rawls. 1991. Effect of soil strength on soil detachment by single raindrops o varying kinetic energy. Soil Sci. Soc. Am. J. 55: 301-307.

Gupta, S. C., J. F. Moncrief and R. P. Ewing. 1991. Soil crusting in mid-western United States. Adv. Soil Sci. (In Press).

Ela, S. D., S. C. Gupta, W. J. Rawls and J. F. Moncrief. 1991. Role of earthworm macropores formed by Aporrectodea tuberculata on preferential flow through a Typic Hapludoll. Proceedings of the ASAE National Symposium on Preferential Flow, December 16-17, 1991, 68-76p.

Freebairn, D. M., S. C. Gupta, and W. J. Rawls. 1991. Influence of Aggregates, microrelief and rainfall intensity on development of surface crusts. Soil Sci. Soc. Am. J. 55: 188-195.

Gupta, S. C. and R. P. Ewing. 1991. Modeling water retention characteristics and surface roughness of tilled soils. Proceeding of the Workshop "Indirect methods of estimating the hydraulic properties of unsaturated soils, Riverside, CA. (Van Genuchten, M. Th. Ed), (in press).

Gupta, S. C., J. K. Radke, J. B. Swan, and J. F. Moncrief. 1990. Predicting soil temperatures under a ridge-furrow system in the U.S. Corn Belt. Soil & Till. Res. 18: 145-165.

Freebairn, D. M. and S. C. Gupta. 1990. Microrelief, rainfall and cover effects on infiltration. Soil & Tillage Res. 16: 307-327.

Freebairn, D. M., S. C. Gupta, C. A. Onstad and W. J. Rawls. 1989. Antecedent rainfall and tillage effects upon infiltration. Soil Sci. Soc. Am. J. 53: 1183-1189.

Schuh, W.M., J.W. Bauder, and S.C. Gupta. 1984. Evaluation of simplified methods for determining unsaturated hydraulic conductivity of layered soils. Soil Sci. Soc. Am. J. 48:730-736.

Gupta, S. C., W. E. Larson, and R. R. Allmaras. 1984. Predicting soil temperatures and soil heat flux under different tillage-surface residue conditions from daily maximum and minimum air temperatures. Soil Sci. Soc. Am. J. 48: 223-232.

Gupta, S. C., W. E. Larson, and D. R. Linden. 1983. Tillage and surface residue effects on upper boundary temperatures. Soil Sci. Soc. Am. J. 47: 1212-1218.

Gupta, S. C., J. K. Radke, W. E. Larson and M. J. Shaffer. 1982. Predicting temperatures of bare and residue-covered soils from daily maximum and minimum air temperatures. Soil Sci. Soc.. Am. J. 46: 372-376.

Gupta, S. C., J. K. Radke, and W. E. Larson. 1981. Predicting temperatures of bare and residue covered soils with and without a corn crop. Soil Sci. Soc. Am.

J. 45: 405-412.

Shaffer, M.J., and S.C. Gupta. 1981. Hydrosalinity models and field validation. pp. 136-181 (Chapter 7). In I.K. Iskander (ed.). Simulating nutrient transformation and transport during land treatment of wastewater. John Wiley and Sons, New York.

Gupta, S.C., and W.E. Larson. 1979. Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density. Water Resour. Res. 15:1633-1635.

Gupta, S. C., M. J. Shaffer and W. E. Larson. 1978. Review of physical/ chemical/ biological models for prediction of percolate water quality. p121-132. In Proc. Internat'l. Symp. Land Treatment of Wastewater, Vol. I. Hanover, NH. 20-25 Aug. 1978.

MARY J. HANKS

Two year time commitment - 2.5% time
Dr. Hanks will contribute to review and supervision of the demonstrations described in Objective F over the two year duration of the project - 2.5% time.

Department: Minnesota Department of Agriculture
Ag Planning & Development Division
Rank: Planning Program Supervisor

Education

Ph.D., Plant Pathology, Iowa State University, Ames, May, 1980. Dissertation: Alternaria Leaf Spot of Maize. Advisor: Dr. Charlie Martinson.

M.S., Plant Pathology, Iowa State University, Ames, February, 1977. Thesis: Inoculum Potential of Helminthosporium maydis Regulated by Inoculum Source. Advisor: Dr. Charlie Martinson.

B.S., Biology, University of Missouri, Kansas City, May, 1974.

Employment History

1991 - present Supervisor for the Energy and Sustainable Agriculture Program, Minnesota Department of Agriculture.
1990 - 1991 Integrated Pest Management Coordinator, Minnesota Department of Agriculture.
1980 - 1990 Plant Pathology Department Head, Northrup King Co.

Professional and Honorary Societies

American Society of Agronomy

American Phytopathological Society

Publications

Fox, C.C., M.M. Rekoske, J. Magsam, M.J. Trainor and Bill Knipe. 1989. A rapid seedling test for evaluation of Phytophthora root rot resistance in alfalfa. Proceedings of the 21st Central Alfalfa Improvement Conference, July, 1989.

Trainor, M.J. and C.A. Martinson. 1981. Epidemiology of Alternaria leaf blight of maize. Phytopathology 71: 262. (Abstract).

Trainor, M.J. and C.A. Martinson. 1978. Nutrition during spore production and the inoculum potential of Helminthosporium mydis Race T. Phytopathology 68:1049-1053.

Tipton, C.L., R.E. Betts, R.V. Paulsen, C.A. Martinson, W.M. Park and M.J. Trainor. 1976. Ophiobolin A production by Helminthosporium maydis in culture and effects on maize seedling tissues. Proceedings of the American Phytopathol. Soc. 3:68. (Abstract).

Weck, E., D. Beckman, D. Mead, C. Bredenkamp and M.J. Trainor. 1991. The use of near-isogenic lines for mapping MDMV resistance in Zea mays L. (In preparation).

Weck, E., D. Beckman, D. Mead, C. Bredenkamp, C. Wangen, C. Perry and M. J. Trainor. 1988. Mapping MDMV resistance in maize. Eucarpia Conference, Poster, Denmark, 1988.

J.A.E. MOLINA

Two year time commitment - 5%
Dr. Molina will contribute to objective E4 over the two year duration of the project - 5% time.

Professor of Soil Science
University of Minnesota

Education
Cornell University, NY: M.S., 1963, Major in Agronomy-Soil Microbiology; Ph.D., 1967, Major in Agronomy-Soil Microbiology, Minor in Biochemistry and Microbiology.

Professional Appointments:
Department of Agronomy, University of Illinois, Urbana-Champaign, 1967-1970.
Department of Soil Science, University of Minnesota, St. Paul, 1970-present.

Publications 1990-92

Molina, J.A.E., A. Hadas, and C.E. Clapp. 1990. Computer Simulation of Nitrogen Turnover in Soil and Priming Effect. Soil Biology and Biochemistry, 22:349-353.

Clay, D.E., C.E. Clapp, J.A.E. Molina, and R.H. Dowdy. 1990. Influence of N fertilization, tillage, and residue management on a soil nitrogen mineralization index. Commun. Soil Sci. Plant Anal. 21:323-335.

Clay, D.E, C.E. Clapp, J.A.E. Molina, and D. Linden. 1990. Soil Tillage Impact on the Diurnal Redox-Potential Cycle. Soil Sci. Soc. Am. J. 54:516-521.

Barak, P., J.A.E. Molina, Aviva Hadas, and C.E. Clapp. 1990. Optimization of an Ecological Model with the Marquardt Algorythm. Ecological Modeling 51:251-263.

Barak, P., J.A.E. Molina, Aviva hadas, and C.E. Clapp. 1990. Mineralization of Amino Acids and Evidence of Direct Assimilation of Organic Nitrogen. Soil Sci. Soc. Am. J. 54:769-774.

Clapp, C.E., J.A.E. Molina, and R.H. Dowdy. 1990. Soil Organic Matter, Tillage, and the Rhizosphere. In Rhizosphere Dynamics. (J. Boc, L. Hammond Ed.). AAAS Selected Symposium 113. pp 55-82.

Clay, D.E., C.E. Clapp, D.R. Linden, and J.A.E. Molina. 1991. Tillage influence on redox potential following rainfall. Soil Tillage Research 22:211-219.

Molina, J.A.E. Nitrogen exchange between organic and inorganic pools in soil-organic residues systems. 1991. BARD report. 110 pp.

Clay, D.E., C.E. Clapp, R.H. Dowdy, and J.A.E. Molina. 1991. Mineralization of fertilizer and soil nitrogen in lime-treated acid soils. Biol. Fert. Soils 12: (accepted for publication 1/91).

Hadas, Aviva, M. Sofer, J.A.E. Molina, P. Barak, and C.E. Clapp. 1992. Assimilation of nitrogen by soil microbial population: NH4 vs. organic N. Soil Biol. Biochem. 24:137-143.

JOHN F. MONCRIEF

Two year time commitment - 5%
Dr. Moncrief will contribute Objective C2 over the two year duration of the project - 5% time.

Associate Professor of Soil Science
Soil Science Department, University of Minnesota

Education:

Ph.D. 1981, University of Wisconsin-Madison, Soil Science major, Botany minor. Dissertation: The effect of Tillage on Soil Physical Properties and the Availability of Nitrogen, Phosphorus, and Potassium to Corn (Zea mays L.). L.M. Walsh and E.E Schulte, co-advisors.

M.S., 1977, Montana State University, Soil Science major, Geology minor. Thesis: The Effect of Irrigation on Soil and Ground Water Quality in the Huntley Irrigation District, Huntley, Montana. Hayden Ferguson, major professor.

B.S., 1975, University of Wisconsin-Stevens Point, Double Major: Soil Science and Natural Resource Management

Employment History:

7/85-present University of Minnesota-Extension Soil Scientist and Associate Professor of Soil Science Appointment is split 80 % Extension and 20% Research

11/81-7/85 University of Minnesota-Extension Soil Scientist and Assistant Professor of Soil Science-Appointment is split 80 % Extension and 20% Research

8/77-11/81: Research Assistant/Associate, University of Wisconsin-Madison.

6/75-8/77: Research Assistant, Montana State University.

Membership in Professional and Honorary Societies (1989)

1. American Society of Agronomy
2. Soil Science Society of America
3. Soil Conservation Society of America
4. Xi Sigma Pi
5. Sigma Xi

Selected Publications

Moncrief, J.F. and E.E. Schulte. 1991. Fertilizer management with conservation tillage systems. 14 pg. In: Implementation of Conservation Tillage Systems in the Midwest (in Press) Midwest Plan Service, Iowa State Univ., Ames Iowa

J.S. Hickman, Moncrief, J.F., and N.C. Wollenhaupt. 1991. The effect of conservation tillage on water quality: fertilizers and pesticides. 15 pg. In: Implementation of Conservation Tillage Systems in the Midwest (in press). Midwest Plan Service, Iowa State Univ., Ames Iowa

Griffith, D., J.F. Moncrief, D. Eckert, J.B. Swan, and D.D. Breitbach.

Influence of soil, climate, and residue on crop response to conservation tillage systems. 19 pg. 1991. In: Implementation of Conservation Tillage Systems in the Midwest. (in press) Midwest Plan Service, Iowa State Univ., Ames Iowa

Gupta, S.C., J.F. Moncrief, and R.P. Ewing. 1991. Soil Crusting in mid-western United States. Adv. Soil Sci (in press).

Gupta, S.C., B. Lowery, J.F. Moncrief, and W.E. Larson. 1991. Modeling tillage effects on soil physical properties. Soil Tillage Research, 20: 293-318.

BRUCE MONTGOMERY

Two year time commitment - 4%
Mr. Montgomery will coordinate and administer objective A over the two year duration of the project - 4% time.

Soil Scientist, Agronomy Services Div.
MN Dept. of Ag.

Education
M.S. Soil Science, North Dakota State University, 1984
B.S. Soil Science, Univ. of Wisconsin-Stevens Point, 1975

Employment History

1990 to present: Minnesota Department of Agriculture
1977-1990: Department of Soil Science, North Dakota State University

Membership in Professional Societies
American Society of Agronomy
Soil Science Society of America

Recent Publications

Costa, J.L., Lyle Prunty, B.R. Montgomery, J.L. Richardson, and R.S. Alessi. 1991. Water quality effects on soils and alfalfa: II. Soil physical and chemical properties. Soil Sci. Soc. Am. J. 55:203-209.

Montgomery, B.R. 1991. Nitrogen in Minnesota Ground Water (MDA's component). Legislative Water Commission Report prepared in a cooperative effort between the Minnesota Pollution Control Agency and the Minnesota Department of Agriculture. St. Paul, MN.

Montgomery, B.R., L. Prunty and E.C. Stegman. 1990. Influence of irrigation and nitrogen management on nitrate leaching losses. In 1990 North Dakota Water Quality Symposium Proceedings. P. 95-114. March 20-21, 1990, Fargo, N.D.

Montgomery, B.R., L. Prunty, A.E. Mathison, E.C. Stegman, and W. Albus. 1988. Nitrate and pesticide concentrations in shallow ground water aquifers underlying coarse textured soils of S.E. North Dakota. In Proceedings of the Agricultural Impacts on Ground Water-A Conference. p. 361-387, March 21-23. Des Moines, Ia.

Prunty, Lyle and B.R. Montgomery. 1991. Lysimeter study of nitrogen fertilizer and irrigation rates on quality of recharge water and corn yield. J. Environ. Qual. 20:373-380.

Prunty, Lyle, B.R. Montgomery, and M.D. Sweeney. 1991. Water quality effects on soils and alfalfa. I. Water use, yield, and nutrient concentration. Soil Sci. Soc. Am. J. 55:196-202.

Vanden Heuvel, R.M., R.G. Hoeft, R.L. Mulvaney, and B.R. Montgomery. 1991. Movement of nitrogen-15 labeled nitrate in large undisturbed columns of poorly drained soil. Commun. Soil Sci. Plant Anal. 22:809-826.

CLIVE F. REECE

Two year time commitment - 10%
Dr. Reece will contribute to objective C1 during the two year duration of the project - 10% time

Department: Soil Science
Rank: Assistant Professor

Education

Ph.D., Soil Science, Washington State University, Pullman, May, 1991. Dissertation: Sparse Plant Community Effects on Soil Water Balance of an Arid Site. Advisor: Dr. Gaylon S. Campbell.

M.S., Soil Science, Cornell University, Ithaca, NY, January, 1988. Thesis: Effects of Flooding on Transpiration and Root Hydraulic Conductance of Conifer Transplants. Advisor: Dr. Susan J. Riha.

B.S., Plant and Soil Biology, University of California - Berkeley, December, 1983.

Employment History

1991 - present Associate member of Graduate Faculty in Soil Science, University of Minnesota.
1991 - present Assistant Professor, Soil Science Department, University of Minnesota.
1987 - 1990 Laboratory Graduate Fellowship, U.S. Department of Energy.
1985 - 1987 Research Associate, Agronomy Department, Cornell University.

Professional and Honorary Societies

Soil Science Society of America
American Society of Agronomy
American Geophysical Union

Publications

Reece, C.F. and S.J. Riha. 1991. Role of root systems in response to flooding Eastern larch and white spruce. Plant, Cell and Environment 14:229-234.

Cortes, P., C.F. Reece and G.S. Campbell. 1991. A simple and accurate apparatus for the generation of a calibrated vapor pressure. Agric. For. Meteorol. 57:27-33.

CARL J. ROSEN

Two year time commitment - 12.5%
Dr. Rosen will contribute to the coordination of Objectives B (5% time) and C1 (5% time) and will assist in supervising field operations in objective D (2.5% time) over the two year duration of the project.

Associate Professor,
Department of Soil Science

PROFESSIONAL SPECIALIZATION:

Soil fertility, Nutrition of Horticultural Crops.

EDUCATION:

Ph.D., University of California, Davis, CA, 1983 (Soil Science); M.S., Penn State University, Univ. Park, PA, 1978 (Horticulture); B.S., Penn State University, Univ. Park, PA, 1976 (Horticulture).
PROFESSIONAL APPOINTMENTS:

1989-present; Associate Professor, University of Minnesota
1983 - 1989; Assistant Professor, University of Minnesota
1978 - 1983; Research Assistant, University of California, Davis
Professional Societies:

Soil Science Society of America
American Society of Agronomy
Crop Science Society of America
American Society for Horticultural Science

SELECTED PUBLICATIONS:

Fritz, V.A. and C.J. Rosen. 1992. Productivity of processing peas as influenced by nitrogen fertilization, Rhizobium inoculation, and fungicide seed treatment. Can J. Plant Sci. (in press).

Finn, C.E., J.J. Luby, C.J.Rosen, and P.D. Ascher. 1991. Evaluation in vitro of blueberry germplasm for higher pH tolerance. J. Amer. Soc. Hort. Sci. 116:312-316.

Rosen, C.J., F. Lauer, D. Birong, and L. America. 1991. Nitrogen and boron utilization by potato: effects on tuber quality and implications for groundwater quality. In: A Report on Field Research in Soils. Agric. Expt. Sta., Univ. of Minn., Misc. Pub. 2 (revised) pp. 23-40.

Rosen, C.J., D. Birong, and G. Titrud. 1991. Phosphorus requirements for irrigated potatoes. In: A Report on Field Research in Soils. Agric. Expt. Sta., Univ. of Minn., Misc. Pub. 2 (revised) pp. 41-43.

Rosen C.J. 1990. Potato fertilization on irrigated soils. Minn. Ext. Serv. AG-FO-3425.

Rosen, C.J., D.L. Allan and J.J. Luby. 1990. Nitrogen form and solution pH influence growth and nutrition of two Vaccinium clones. J. Amer. Soc. Hort. Sci. 115:83-89.

Bierman, P.M., C.J. Rosen and H.F. Wilkins. 1990. Leaf edge burn and axillary shoot growth of vegetative poinsettia plants: Influence of calcium, nitrogen form, and molybdenum. J. Amer. Soc. Hort. Sci. 115:73-78.

Rosen, C.J. 1990. Incidence of leaf tipburn in cauliflower as affected by cultivar, calcium sprays, and nitrogen nutrition. HortScience 25:660-663.

Finn, C.E., C.J. Rosen, and J.J. Luby. 1990. Nitrogen form and solution pH effects on root anatomy of cranberry. HortScience 25:557-559.

MARK W. SEELEY

Two year time commitment - 6%
Dr. Seeley will contribute to objectives E2 (2% time) and E3 (4% time) over the two year duration of this project.

Extension Climatologist
Soil Science Department

Employment History

Assistant Professor, 1978 - 1982 (100% Extension)
Associate Professor, 1982 - 1989 (80% Ext. 20% Res.)
Professor, 1989 - present (80% Ext. 20% Res.)
Sabbatical leave to United Kingdom, Ministry of Agriculture (Feb. 89 to Feb. 90)

Recent Articles, Presentations and Publications:

Some Applications of Minnesota's Centennial Climate Data Base. 1992. with Jim Zandlo at Minnesota Water '92. Mpls Convention Center.

Weather, Climate and Cereal Growth. 1992. Minnesota Small Grains Institute, Red River Valley Winter Shows, Crookston,

Climatic Cycles: Uncertainties for 1991 and Beyond. 1990 Soils Fertilizer and Agricultural Pesticides Short Course. Mpls Convention Center.

Seeley, M.W., J.M. Graham and C.A. Schrader. 1990. The Importance and Utilization of Agricultural Weather Information In Minnesota: A Survey. J. Agron. Ed., vol. 19, No. 1:86-91.

Seeley, M.W. 1990. Climatic Considerations Relevant to the Use of Growth Regulators in Winter Cereals. British Ministry of Agriculture MAFF/ADAS Tech. Note 26 (38 pp)

Managing Agricultural Environments of North-Central Minnesota Sandy Soils

Final Summary Report Submitted to the
Legislative Commission on Minnesota Resources

Department of Soil, Water, and Climate
University of Minnesota

and

Minnesota Department of Agriculture

July 1, 1995

1993 3(h)

Date of Report: July 1, 1995

LCMR Research Work Program 1993 - Summary

I. Project Title: Managing Agricultural Environments of North-Central Minnesota Sandy Soils

Program Manager: Dr. H.H. Cheng, Head
Soil Science Department
University of Minnesota
St. Paul, MN 55108
Phone: (612) 625-9734 FAX (612) 625-2208

A. Legal Citation: M.L. 93, Chpt. 172, Sect. 14, Subd. 3(h) Agriculture
Total Biennial LCMR Budget: $480,000
Balance: $0

Appropriation Language as drafted 7/27/92: This appropriation is from the future resources fund to the commissioner of agriculture for a contract with the University of Minnesota to develop improved management strategies for water, nitrogen, and herbicide use on sandy soils in north-central Minnesota.

B. LMIC Compatible Data Language: not applicable
C. Status of Match Requirement: not applicable

II. Project Summary: This project will address water quality concerns arising from corn and potato production on sandy soils in north-central Minnesota by developing improved management strategies for water, nitrogen, and herbicide use. Crop production on sandy soils is believed to have led to increased nitrate and herbicides in the groundwater of north-central Minnesota. On the other hand, crop production, especially potato production, is extremely important to the economy of the region. The primary goal is to help provide improved nitrogen and herbicide management options for farmers that maintain profitability but reduce the potential for contamination of groundwater from nitrate and herbicides from agricultural sources. This will be accomplished through research and education in north-central Minnesota.

III. Statement of Objectives:
A) Evaluate current agricultural management practices in north-central Minnesota; B) Refine diagnostic criteria to predict in-season nitrogen needs for irrigated potatoes; C) Improve best management practices for irrigated potatoes and corn; D) Evaluate herbicide losses to groundwater under irrigated potato production; E) Develop computer models for BMPs that consider movement of water nitrogen, and herbicides; F) Disseminate Information.

IV. Research Objectives

A. Title of objective: Evaluate current agricultural management practices in north-central Minnesota.

A.1. Activity: Grower survey for information on irrigation amounts and timing, fertilizer types and rates, soils test values, yields and yield goal setting, pesticide types and application rates, crop rotations, tillage practices, manure rates and application times, and nitrogen credits for alfalfa and manure sources.

A.1.a. Context within project: Approximately 40% of the state's potato production acres (70,000-80,000 acres statewide on an annual basis), are grown in the irrigated coarse-textured soils. Potato producers representing three geomorphic regions will be interviewed. These regions, which account for approximately 60% of the state's irrigated potato acreage, are: the Detroit Lakes Pitted Outwash Plain; the Park Rapids-Staples Outwash Plain; and the Mississippi Valley Outwash.

A.1.b. Methods: Less than 20 producers account for a high percentage of the potato acreage in these three regions. All potato producers in these particular geographic locations will be requested to participate in the inventory process. Growers will be requested to provide information on irrigation amounts and timing, fertilizer types and rates, soil testing, yields and yield goal setting, pesticide types and rates, crop rotations, tillage practices, manure rates and application times, and nitrogen credits for alfalfa and manure sources. In cooperation with the Minnesota Irrigators Association and Minnesota Extension Agents, growers will be interviewed through a one-on-one type process. This is the only feasible method for collecting information on such a high level of detail.

In order to fully understand the dynamics of nitrogen cycling on the coarse-textured soils in these regions, information will also be needed for dryland agriculture, thus, a survey or farm inventory assessment effort will be designed to focus on dryland agriculture.

A.1.c. Materials: Questionnaires and Extension bulletins

A.1.d Budget: $25,000 **Balance:** $0

A.1.e Timeline:
Irrigated Potato Inventory

	7/93	1/94	6/94	1/95	6/95
Design inventory questions/forms	xx				
Data base programming		xx			
Establish sampling populations			xx		
One-on-one interviews				xx	
Summary, publications of results				xx	

Nonirrigated Agricultural Survey				
Design inventory questions/forms	xx			
Data base programming		xx		
Establish sampling population			xx	
One-on-one interviews/mailouts			xx	
Summary, publication of results				xx

A.1.f. Status: Current Nutrient Management Practices on Non-Irrigated Central Sands. Fifty-eight farms, covering over 31,000 acres, participated in the **FA**rm **N**utrient **M**anagement **A**ssessment **P**rogram (**FANMAP**) with staff from the Minnesota Department of Agriculture. Producers volunteered 2-4 hours of their time to share information about their farming operation. Producers were carefully selected to represent a wide diversity of management skills and farm characteristics. The overall purpose of the program was to develop a clear understanding of current farm practices regarding agricultural nutrients and utilize this knowledge for future water quality educational programs.

Nitrogen management on the Central Sands is challenging due to the nature of the soils and additional management skills required to manage organic N inputs. Manure accounts for approximately 33% of the 'first year available' N; legumes account for another 17%. Obviously proper crediting of both of these sources is needed to successfully manage N on these outwash sands. Yield goals varied tremendously on these outwash soils due to the wide range of organic matter content and available moisture holding capacity. The overall corn yield goals were 70 bu/A. Consequently, the nutrient inputs in general were significantly lower than most other regions of the state.

On corn acres where no previous manure or legume credits existed to confound the rate selection process, producers appear to be in excellent agreement with recommendations that were made by UM/MES. Corn acres which were above or below the UM recommendations were equally distributed.

Overall, producers reduced N fertilizer inputs following "first year" alfalfa by 17 lb/A. However, additional reductions (20-30 lb/A) could be made with a low probability of yield loss. One of the difficulties in the data collection process was obtaining reliable alfalfa information prior to stand termination. It appears that producers need the assessment tools for determining alfalfa stand densities and record keeping systems to aid in more effectively capturing alfalfa credits.

Producers were basically reducing commercial N inputs by 24 lb/A in scenarios where previous manure applications were made to non-legume crops such as corn. Producers were under-estimating the value of the manure by approximately 25 lb/A. It is a common practice to apply manure to old alfalfa stands which are followed by corn in the rotation. In this scenario, producers were found to reduce their commercial inputs by approximately 17 lb/A. However the combination of alfalfa and manure credits, coupled with the fertilizer (average of 40 lb/A), resulted in over-applications of 70 lb/A. In these situations, only a starter N application should be applied and would trim 20 to 30 lb/N/A from the N budget. Due to the low yield potentials of these soils, all the N requirements for corn will be supplied from alfalfa stands of 2 plants/ft or denser. Producers could capture a higher percentage of the "fertilizer replacement value" by applying the manure into other corn rotations. Approximately 50% of the corn acres did not receive any manure application so there is ample locations to apply the manure. From a water quality perspective, the most significant impacts could be made by improving the N crediting process in this particular cropping scenario.

Proper timing of N applications is one of the key management strategies that producers in this region can implement to minimize N leaching losses. Producers have been encouraged to avoid fall application on any coarse-textured soils. FANMAP determined that fall application of N was extremely rare; spring preplant and starter N accounted for 56% of applied N fertilizer with the remaining balance sidedressed. Timing and source selection of N fertilizers appeared to be in excellent agreement with current BMPs developed by MES in conjunction with MDA. A very high percentage of the N fertilizers were ammonium based products.

This area has a high diversity of storage/collection systems, most of which provide some opportunity for storage. The process of manure crediting is greatly simplified with manure storage systems that allow for a minimal number of land application events. Over 80% of the N retained after storage originated from a variety of systems that allowed for some storage benefits. In previously studies by the MN Extension Service, the nutrient value from manure has been found to be highly variable. Manure testing needs continual promotion as a fundamental part of a nutrient management plan. Only 10% of the producers had tested their manure previously to this project.

There were some very positive findings from this study. There is strong evidence that producers are voluntarily adopting the educational materials and strategies developed by the University of Minnesota/MN Extension Service. It is also evident that promotional activities need to continue and be specifically targeted to deliver the most recent technology and recommendations. Strong similarities exist in all existing FANMAP projects: producers are generally managing commercial N inputs successfully (although frequently using outdated recommendations) but continually under-estimate the N credits associated with manure and alfalfa inputs.

Current Nutrient Management Practices For Irrigated Potatoes on Sandy Soils. Twenty-four potato farmers covering over 19,000 acres, participated in the **FA**rm **N**utrient **M**anagement **A**ssessment **P**rogram (**FANMAP**) with staff from the Minnesota Department of Agriculture. Producers volunteered 2-4 hours of their time to share information about their farming operation. Producers were carefully selected to represent irrigated potatoes on sandy soils. The overall purpose of the program was to develop a clear understanding of current farm practices regarding agricultural nutrients and utilize this knowledge for future water quality educational programs.

Nitrogen management for potato growers on sandy soils is challenging due to the nature of the soils and additional management skills required to manage irrigation scheduling. The overall potato yield goals were 410 cwt/A and N inputs came primarily from commercial fertilizer. Only one grower had N contributed from manure and less than 5 lbs/A were contributed from previous legumes. Cover crops were used extensively for early and medium maturity potatoes; consistent with current BMPs.

Overall, producers were generally over applying N by 48 lbs/A according to recommendations from the U/M. In addition it appears potato growers could reduce their N rates in starter fertilizers by 35% from 67 lbs/A to the recommended 40 lbs/A according to U/M recommendations. Research on early maturing potatoes, especially the new varieties, will provide further assistance to potato growers. Proper timing of N applications is one of the key management strategies that producers in this region can implement to minimize N leaching losses. Producers have been encouraged to avoid fall application and research suggests this practice is being endorsed. Timing and source selection of N fertilizers appeared to be in excellent agreement with current BMPs developed by MES in conjunction with MDA. A very high percentage of the growers were using multiple split applications and N applications through fertigation were consistent with recommended practices also.

Soil testing was done on 68% of the potato acres providing information to assist the growers in correct fertilizer application amounts. In regard to Phosphorus, growers seem to be over applying by approximately 92 lbs/A according to U/M recommendations. Here again, research on additional varieties and early maturing potatoes will provide assistance to the potato growers.

There were some very positive findings from this study. There is strong evidence that producers are voluntarily adopting the educational materials and strategies developed by the University of Minnesota/MN Extension Service. It is also evident that promotional activities need to continue and be specifically targeted to deliver the most recent technology and recommendations.

B. Title of objective: Refine diagnostic criteria to predict in-season nitrogen needs for irrigated potatoes

B.1. Activity: Field experiments will be conducted using various N treatment regimes to define petiole sap nitrate critical values suitable for predicting nitrogen fertilizer needs.

B.1.a. Context within the project: Conventional N management for potatoes on irrigated soils consists of N fertilizer applications at planting, emergence, hilling, and post-hilling. One rational approach for managing N to reduce nitrate leaching would be to limit applications prior to hilling when plants are small and then base post-hilling N applications on a diagnostic N test. The emphasis of this objective is to calibrate the petiole sap nitrate test to more accurately predict N needs of irrigated potatoes during the growing season.

B.1.b. Methods: A two-year field experiment using the Russet Burbank cultivar (the most common cultivar used on irrigated soils in Minnesota) will be conducted to calibrate the nitrate sap test for diagnostic purposes. Data generated under this objective will be used to define critical sap nitrate concentrations that will serve as an indicator of N needs in potatoes. Treatments will consist of a 0 N control and eight N management strategies based on N applications at various times through the growing season. The main calibration experiment will be conducted at the Sand Plain Research Farm in Becker, MN, a site near an area where large acreages of irrigated potatoes are grown. Additional experiments to validate the sap test will also be conducted at Staples Irrigation Center and a grower site at Park Rapids MN (see objective C.1.). For these smaller experiments, a typical grower rate of nitrogen application (270 kg N/A) and a treatment based on the sap test will be tested. Planting, emergence, and hilling N applications will be made with an ammonium based fertilizer. All post-hilling applications will be made at two week intervals with urea-ammonium nitrate solution. A 34 kg ha^{-1} rate of N is typical of that used by growers when supplemental N is applied posthilling and will be used in the current experiment when additional nitrogen is required. Each plot will consist of six, 9-meter rows consisting of two border rows, two sample rows, and two harvest rows. The experimental design will be a randomized complete block with 4 replications. The checkbook method will be used to schedule irrigation. At harvest, tubers will be separated and graded according to marketability. Yield data will be subjected to standard analysis of variance procedures.

B.1.c. Materials: Potato seed, fertilizer, equipment, nitrate electrodes, laboratory reagents/supplies.

B.1.d. Budget: $59,500 **Balance:** $0

B.1.e. Timeline	7/93	1/94	6/94	1/95	6/95
Establish field plots	xxxx		xxxx		
Collect petiole samples	xxxx		xxxx		
Sample analysis		xxxxx		xxxx	
Develop critical sap nitrate levels		xxxxxxxxxxxxx			

B.1.f. Status: Two nitrogen (N) management studies on irrigated potatoes were conducted during 1993 and 1994 at the Sand Plain Research Farm in Becker, MN to evaluate the effects of various N management strategies on N use and nitrate movement under irrigated Russet Burbank potatoes. A second objective was to calibrate a quick petiole nitrate sap test for determining nitrogen status of the crop and predicting nitrogen needs.

In 1993, tuber yield increased with increasing N rate up to 240 lb N/A, with the greatest increase occurring between the 0 and 120 lb N/A rate. At equivalent N rates, use of post-hilling N applications tended to result in larger tubers compared to applying all the N up to hilling. Leaching of N was related more to rate of N applied than timing of application. Final tuber yields with urea as the N source were similar to those with ammonium nitrate as the N source, although early plant growth with ammonium nitrate was greater than with urea. The early response to ammonium nitrate may have been due to cooler temperatures, which may have retarded conversion of urea to ammonium and nitrate. Petiole nitrate increased with increasing N rate and with post-hilling N applications. Petiole nitrate decreased through the season at a faster rate with treatments that did not involve post-hilling N application compared to those that did. The correlation between petiole sap nitrate and nitrate in petioles based on dry weight was highly significant with an r-squared of 0.92. The slope and intercept of the line was similar to the results from 1991 and 1992, suggesting that the tentative sap critical values based on previous year's calibration used to predict N needs were appropriate.

Overall, 1994 was a low leaching year. However, insect pressure from Colorado potato beetle and aphids caused early dieback and limited yields. Tuber yield increased with increasing N rate up to 120 lb N/A with little response above this rate. The relatively low response to N above 120 lb N/A may have been due to lack of N leaching and poor late season growth due to insect/disease pressure. At equivalent N rates, there were no significant differences in tuber yield or quality due to timing of N application. Hollow heart increased with increasing N rate, but was not affected by post-hilling N application. Higher concentrations of nitrate in soil water at the 4 ft depth were found in the row compared to between the row for most treatments. Leaching of N was related more to rate of N applied than timing of application. Final tuber yields with urea as the N source were similar to those with ammonium nitrate as the N source. Petiole nitrate increased with increasing N rate and with post-hilling N applications. The quick tests used reflected the changes in petiole nitrate with N treatment. Use of petiole testing in 1994 predicted an N response in the 120 and 160 lb N/A treatments, yet a response to additional N was not observed. As mentioned above, the lack of response was probably due to early dieback. The results from 1994 indicate that an integrated approach to N management needs to be taken. If plants are dying of insect and disease pressure then, additional N may not be beneficial even if a need is indicated by the petiole test.

The overall results from this calibration study have helped to improve diagnostic criteria for determining N needs for irrigated Russet Burbank potato. Calibration studies still need to be conducted for other varieties, but it should be noted that Russet Burbank is the dominant variety grown in Minnesota (about 50 to 60% of the acreage). Approximate sap nitrate-N sufficiency ranges for Russet Burbank based on the calibration study are: 1300-1600 ppm for initial vegetative growth/tuber initiation; 900 to 1200 ppm for tuber growth/bulking; and 550 to 800 ppm for tuber bulking/maturation. These diagnostic criteria have been incorporated into Nitrogen Best Management Practices for irrigated potatoes. The overall effects of N fertigation on potato production and nitrate leaching in irrigated potatoes are evaluated under Objective C.

C. Title of Objective: Improve best management practices for irrigated potatoes and corn

C.1. Activity: Evaluate petiole sap-based N management on the basis of nitrate leaching, marketable yield, and costs and compare to conventional N management.

C.1.a. Context within the project: The petiole sap N criteria developed in Objective B will form the basis of a best management practice for irrigated potatoes. For early season sap tests, N applications could be made in the hill; however, because field operations are more difficult once the canopy closes, N applications based on the post-hilling sap tests will need to be applied either through the irrigation system or as a non-burning foliar spray. Water and N movement within and between rows must be measured to determine the impact of sap nitrate-based N applications on nitrate losses from the system. Data from this objective will be used for computer model validation in Objective E.

C.1.b. Methods: Sap based N management will be evaluated on the basis of nitrate leaching, marketable yield, and costs in a two-year experiment using the Russet Burbank potato cultivar. Less nitrate leaching without yield reduction relative to conventional N management will be the desired characteristics of new N management strategies based on petiole nitrate sap analysis. Detailed small plot experiments will be conducted at Staples and Becker Research stations in conjunction with objective B.

Nitrogen management demonstrations on growers fields will also be conducted over a two year period near Becker and Park Rapids, MN.

C.1.c. Materials: Suction cup samplers, pressure transducer equipped tensiometers, laboratory supplies, and field dataloggers will be needed to carry out this experiment.

C.1.d. Budget: $54,500 **Balance:** $0

C.1.e. Timeline	7/93	1/94	6/94	1/95	6/95
Establish field plots	xxx		xxxxx		
Collect petiole samples	xxx		xxxxx		
Measure soil water nitrate	x		xxxxx		
Measure soil water flux	xxxx		xxxxx		
Analyze data and costs		xx		xxxxx	

C.1.f. Status: Research Plots at Staples. Experimental plots were established at the Staples Irrigation Center during the 1993 and 1994 growing seasons. Two nitrogen fertilization schemes were compared - one employing the use of solid fertilizer up through the hilling stage (conventional) and the other using lower rates of solid fertilizer through hilling followed by N fertigation applications based on the sap test. Water distribution patterns at the soil surface were monitored by use of plastic cups. Canopy water retention and stemflow were calculated. Soil water samples were collected from suction cup samplers located in the furrow and in the row. Samples were tested for nitrate concentration. Water movement was calculated by monitoring the soil matric potential. From these values the N loss below the rooting zone was calculated for both the plant rows and furrows between rows. For comparison purposes, nitrate leaching was calculated using an N budget where unaccounted for N was included with leached N. The following N budget was used: Fertilizer N input + Mineral soil N in the spring + Mineralized N - Plant N - Residual soil N at harvest = N leached + N unaccounted for. This budget was used to determine if processes other than leaching (denitrification, volatilization, immobilization) need to be included/measured.

Measurement of throughfall patterns through the showed that the plant canopy initially shed water similar to an umbrella, and that the quantity of water held by the plant canopy and channeled down stems was insignificant. Early in the growing season, plant vines were upright resulting in more water being deposited in the furrows than the rows. Later in the season, when the vines slumped and leaf area was lower in the row than in the furrow, more water was deposited in the row than in the furrow. The implication of this finding is that fertigation applications made too early in the season may result in N losses from the furrow, especially if roots are not present in the furrow.

Measured water leaching over the growing season showed that more was lost from the furrow than the row. There was no significant difference between row position with respect to N loss, indicating that nitrate concentrations were higher in the row than in the furrow. A greater quantity of N was lost with the conventional treatment in 1993. There were no significant differences between the two treatments in 1994, although the trend was similar to that in 1993. These results indicate that the petiole sap test is a useful tool to schedule N fertigation applications and that fertigation does not increase overall leaching of nitrate during the growing season.

Comparison of nitrate leaching calculated by an N budget with measured nitrate leaching showed a large discrepancy between the two methods, with measured nitrate leaching much lower than calculated nitrate leaching. Assuming that measured nitrate leaching losses were reasonably accurate, these results indicate that processes not directly measured such as immobilization, denitrification, and volatilization (unaccounted for N) need to be measured to develop a meaningful N budget.

On-farm demonstrations. Improved N management strategies were demonstrated in growers fields during the 1993 and 1994 growing seasons. In 1993, two potato pivots near Park Rapids (Hubbard County) and one potato pivot near Becker (Sherburne County) were monitored. In 1994, one potato pivot near Park Rapids and one near Becker were monitored. Russet Burbank was the potato cultivar used in all demonstrations. The original plan was to manage half of each field according to conventional grower procedures and the other half using improved N management strategies. The improved strategies included: reduced N at planting (< 40 lb N/A), reduced N at emergence (70-90 lb N/A), reduced N at hilling (70-90 lb N/A), post-hilling N applications would be based on the sap test. In the past, conventional grower procedures included 60 to 100 lb N/A at planting, and 80 to 100 lb N/A at emergence and hilling. Post-hilling applications were not usually based on any diagnostic criteria. Unfortunately, we were unable to get the growers to follow these conventional procedures in our demonstrations. Growers more or less mimicked the improved management practices on both sides of the field. There were some differences in N management between either side of the field, but not as different as we had hoped. The demonstrations were still useful because other growers in the areas were made aware that these improved practices did not detrimentally affect yield and quality.

Overall results of the five demonstrations showed that 30 lb N/A less can be applied using improved practices with no negative effects on yield or quality. This saving in N fertilizer (about $600/100 acres) would more than offset the cost of monitoring a 100 acre field for petiole nitrate.

Use of both the demonstrations and field experiments from objectives B and C has resulted in the development of Nitrogen Best Management Practices for irrigated potatoes. The suggested BMPs developed have been sent out to growers for discussion and once the final revision is made, the BMPs will be adopted for use by the Minnesota Department of Agriculture and Minnesota and other state agencies.

C.2. Activity: Various nitrogen sources (manure and fertilizer) will be compared as to their efficiency of plant recovery and leaching losses under irrigated corn production. Soil type and climate effects will be evaluated.

C.2.a. Context within the project: Dairy and poultry livestock operations are an important part of the economy in North-central Minnesota. Environmentally sound manure and fertilizer nitrogen utilization from these farming enterprises is imperative. Preliminary data have shown performance of anhydrous ammonia to be inconsistent when compared to other sources of N (urea-ammonium nitrate solutions, dry urea, and animal manures) in plant recovery and leaching losses. It is the cheapest fertilizer source however. This objective will evaluate these sources of N under various precipitation distribution on sandy irrigated soils.

Data from this objective will be used for computer model validation in Objective E.1.

C.2.b. Methods: Corn will be grown in rotation with potatoes. The experimental design will be a randomized complete block with five N sources: urea, anhydrous ammonia, urea-ammonium nitrate solution, and turkey manure. All nitrogen will be applied using current best management recommendations for timing and N rate. Corn and potato response will be characterized by measuring grain yields and total N uptake. Nitrate leaching losses will be estimated.

C.2.c. Materials: suction samplers and laboratory supplies.

C.2.d. Budget: $54,500 **Balance:** $0

C.2.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Establish treatments	xxxx		xxxx		
Collect soil water data	xxxx		xxxx		xxxx
Collect plant data	xxxx		xxxx		xxxx
Analyze data		xxxx		xxxxxxxxx	

C.2.f. Status: Sandy glacial outwash soils in central Minnesota are being cropped more frequently with potatoes. The presence of shallow groundwater tables coupled with coarse textured soils makes this region an especially high risk area for water quality degradation. Maintenance of maximum potato yields may be leading to further contamination of groundwater quality by agricultural chemicals. Nitrate has been found to be the major pollutant associated with groundwater in areas of intensive agriculture.

Minnesota, the second largest turkey producer in the U.S. has a surplus of turkey manure with high N content. This turkey manure may be a useful source of N for potato production and may result in reduced leaching potential for groundwater degradation by nitrates. Granular urea in split applications is the N management typically used by potato farmers in Minnesota. Other N sources used in the area, either on corn or potato, are anhydrous ammonia (AA) and urea-ammonium-nitrate (UAN) solution. To test which N source produces highest yield with lowest impact to the environment, we conducted a field experiment at Staples, MN.

The specific objectives of this two year study were to determine the effect of four different N sources in a corn and potato rotation on crop yield and quality, plant N uptake, and N leaching losses below the root zone.

In 1993, rainfall was plentiful except for a 20 day period beginning in late July extending into early August. Six cm of irrigation was supplied at four discrete times. Measured values include water from rain and irrigation. Estimated values include a daily summation of water use taken from a table in the Checkbook Method of Wright and Bergsrud, 1980. It has been shown by Dylla et. al. (1980) that the water use tables of Wright and Bergsrud are comparable to estimates obtained by more precise methods. Therefore, knowing total applied water, plant use, and soil storage (six cm),the resultant parameter (leachate) can be estimated. Corn was supplied 66.1 cm, used 36.3cm, and leached 31.5 cm of water in 1993. The remaining water (1.7 cm) is accounted for in soil storage. Corn in 1994 was supplied with 38.9 cm, used 38.0 cm, and leached 6.2 cm in 1994. No water excess occurred after 24 June (175), 1994. Irrigation equipment malfunctions caused a late season deficit to reach 5.3 cm (88 % of the available water holding capacity (AWHC) in 1994, perhaps limiting yield of both corn and potato.

The potato water summary was very similar to the corn summary for individual years. Potato used three cm less water than corn in 1993 and 1 cm more water than corn in 1994. Because rainfall and irrigation were the same for corn and potato, the only other different variable is leachate. In 1993, 31.5 cm leached past the root zone and in 1994, 4.5 cm leached leading to the qualitative conclusion of calling 1993 a leaching year and 1994 a non-leaching year.

No effects of N source were observed in 1993. Grain yields were higher than the control. Stover yields were not different than the control in all treatments. Turkey manure and urea yielded the most grain in 1994. Stover harvested on turkey manure plots was the only treatment not different than control. Yields in 1994 were higher than 1993 except for the control. Turkey Manure or urea split applied are acceptable N sources for corn on irrigated sandy soil.

Plots with turkey manure, urea, and anhydrous ammonia gave highest marketable tuber yield in 1993. The urea-ammonium nitrate solution treatment (UAN) yielded significantly less marketable tubers than granular urea and AA, but was not significantly different than the turkey manure treatment. The urea treatment produced the most tubers but was not significantly different than total yields under turkey manure and AA fertilization. The urea treatment gave greatest vine yields while other N sources produced significantly less vines.

In 1994, there was no effect of N source in marketable tuber yield. The turkey manure, urea, and anhydrous ammonia treatments had highest total tuber yield. At harvest in 1994, vines in the turkey manure plots were still green, while vines in other treatments had died.

The difference between total and marketable tuber yields give an estimate of non-marketable tubers which corresponds to low quality. In 1993, the difference between total and marketable tubers is lowest (2.3 Mg ha^{-1}) in the AA treatment indicating higher production efficiency. Excluding the control, in 1994 turkey manure was the most efficient N source.

Turkey manure is an acceptable N source for tuber yield and produces high quality tubers. Nitrogen sources other than 28% can be used at similar rates to achieve similar yield. Late season N release occurs with turkey manure evident from vine data in 1994.

Having established a method for estimating water excess (assuming all excess is lost to subsurface reservoirs), we can calculate the volume of water per hectare. Multiplying the excess volume by the concentration of nitrogen from suction cup samplers gives the values with units of kg ha^{-1}. In 1993, before suction cup installation, a large leaching event on 24 May. Thirteen cm of unsampled excess water leached through the profile. The assumption of a concentration of 10 mg N L^{-1} based on soil solution concentrations from a nearby field, yields an event with calculated loss of 13 kg N ha^{-1}. Otherwise, it appears that nitrate is leached more under potato than corn. It is curious to note that the total nitrogen leached under the potato control was higher than all other treatments under corn in 1993.

Again, in 1994 as in 1993, nitrogen concentrations under potato were higher than corn, probably due to differences in rooting depths. Several dates with predicted leaching events on potato and not corn indicate periods which potato water use is greater than that of corn. The point where the ratio of potato:corn water use is one, was on 8 August,1993 and on 19 July,1994. Prior to these dates potato use is higher and after these dates corn use is higher. Generally, by these dates both corn and potato are at the onset of maturity and senescence and plant water use begins to decrease.

Comparisons of N lost under split urea application and turkey manure treatments indicate that in a leaching year, 1993, the mineralization of turkey manure creates excess nitrogen capable of being leached later in the growing season if not taken up by plants. This may be the case on 20 August, 1993, 30 kg ha^{-}

^{1}(almost half the treatment total) was leached in one event.

Another factor determining leachability of N is timing of the fertilizer application. On 11 July, 1993, 15 days after side-dressing of urea, 17 kg ha^{-1} leached with 2 cm water excess. During the last leaching event of the growing season on 1 September, 1993, the control treatment lost more N than urea treatments but lost less than the turkey manure treatment. This implies that the same mechanisms for soil organic matter mineralization may also regulate turkey manure mineralization.

Cumulative N losses during the 1994 growing season indicates that less leaching occurred over 1993. No leaching events occurred after June. The largest events leached less than 2 cm carrying 2 to 17 kg N ha^{-1}. Turkey manure contributes more to groundwater degradation than urea and control treatments.

In conclusion, nitrogen sources other than urea-ammonium nitrate solutions produced equivalent yields in a corn/potato rotation. Yields with urea-ammonium nitrate on the same soil tended to be lower than with other N sources. During the first half of the growing season, potato evapotranspiration exceeded corn ET, therefore less leaching occurred under potato. Later in the growing season, decreased potato water use was responsible for higher nitrogen fluxes past the root zone. Mineralization of turkey manure can contribute to nitrate contamination of leached water later in the growing season.

D. Title of Objective: Evaluate herbicide losses to groundwater under irrigated potato production.

D.1. Activity: Assess the fate and transport of herbicides used in irrigated potato productions under the management practices and soil and climatic conditions of the north-central Minnesota sand plain region and develop risk indices for these herbicides.

D.1.a. Context within the project: Use of herbicides for weed control is currently an integral part of the management practices in irrigated potato production. Since weeds are a major threat to potato production efficiency, effective weed control will be essential in the development of best management practices. If herbicides are to be used, it is crucial to determine the fate and transport of these chemicals as affected by the climatic and soil conditions and the fertilizer and soil management practices of the study region. The data generated will be used for testing the validity of the computer models developed under Objective E.

D.1.b. Methods: The field plots set up for evaluating the BMP for irrigated potato production (under Activity C.1.) will be used for assessing the fate of herbicides under the same conditions. Herbicides in common use in irrigated potato production (e.g.,linuron, metolachlor, and metribuzin) will be applied at standard rates, and soil and water samples taken for the nitrogen BMP studies under Activity C.1. will also be used to monitor the fate and transport of herbicides under the same field conditions. Extensive soil sampling will also be conducted at the end of the growing season and before the beginning of the following growing season. Laboratory methods will be tested for their efficiency in recovery and detection of residual herbicides in the soils. The data will be used to test the validity of the simulation model LEACHM for determining their risk indices.

D.1.c. Materials: The equipment needed for field sampling will be the same as those used for Activity C.1. Laboratory supplies.

D.1.d. Budget: $80,000 **Balance:** $0

D.1.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Field plot setup:	xxxx				
Field sampling/measurement:	xxxx		xxxx		xxxx
Laboratory analyses:	xxxxxxxxxxxxxxxxxxxxxxxx				
Result evaluation/model validation:	xxxxxxxxxxxxxxxxxxxx				

D.1.f. Status: We have completed a two-year study to monitor the fate and transport of herbicides in soil in a center-pivot irrigated field under commercial potato production at Park Rapids, Minnesota. This field site is the same as that described under C.1 for nitrate monitoring under the irrigated potato demonstration project. The soil at the experimental site is a Verndale sandy loam. Metolachlor and metribuzin were surface-applied according to standard production practices over the entire field. During the first year, 24 sampling stations were installed in the field which was set up to compare a conventional and a modified nitrogen fertilizer management strategy. Each water sampling station consisted of a set of stainless steel suction tubes buried at 135 cm (4.5 ft) below the soil surface either directly underneath a potato hill or underneath a row between the hills. Soil samples were collected in 15-cm (6-inch) increments down to the 90-cm (3-ft) depth. Water samples were collected one day after each significant rainfall event during the growing season, which is sufficient time for free drainage to complete in this soil. On each sampling date, not all stations yielded sufficient water for a proper analysis. Only those stations yielded more than 50 mL of water were stored for determination of the metribuzin and metolachlor concentrations. During the growing season of 1993, water samples were collected on 19 occasions. In addition, soil samples were taken from the differently managed parts of the study field 5 times: at planting, twice during the growing season, immediately after harvest, and one year later just before the next growing season.

Results from analyses of the 1993 samples indicate that both metolachlor and metribuzin were present sporadically at detection-limit levels of a few ppb concentration in some water samples. These occurrences were occasional and without any regular pattern. No detectable amount of metribuzin or metolachlor was found in any of the soil samples, except one, below the 30-cm depth. The detection limit of soil analysis is 5 ppb. Water analysis is more sensitive than soil analysis since we can analyze a large volume of water more readily than a large volume of soil. The quantity of pesticides detected in water, if converted to the soil basis, would be below the detection limit of the most sophisticated analytical instrument available.

To validate the observations made under field conditions of 1993, the monitoring study on herbicide movement under irrigated potato was repeated during the 1994 growing season in a field adjacent to the 1993 study field in Park Rapids. The 1994 potato field was in rye grass in 1993. Although the 1993 data showed a rapid initial dissipation of both metribuzin and metolachlor in the soil under field conditions, soil sampling frequency was insufficient to estimate the kinetics of dissipation or to ensure that no rapid leaching of these two chemicals took place. In the 1994 study, soil samples were taken at three-day intervals and analyzed for metribuzin and metolachlor contents without long delays. The results obtained verified the previous year's observations in that the dissipation of these two chemicals were initially rapid, with little or no observed downward leaching during the growing season.

To further verify the field observations, laboratory experiments were designed to study the degradation characteristics of metolachlor and metribuzin in soil taken from the same field and incubated under controlled conditions. Although environmental variables affecting herbicide degradation may not be the same under laboratory conditions as under field conditions, potential for degradation can be better assessed under controlled conditions, as laboratory studies provide data on degradation without complicated by leaching of the chemicals which can take place under field conditions. The kinetics of degradation observed under controlled laboratory conditions were similar to those observed in the field. Both herbicides degraded rapidly initially, but more slowly with time. Metolachlor appeared to degrade slower than metribuzin both in the laboratory and under field conditions.

The data obtained in the present study were consistent with those reported in earlier studies which were conducted at Becker, MN on a Hubbard loamy sand soil, as well as with other reported findings in the literature (see the detailed report for references). Neither herbicide was transported to any significant degree, but both tended to remain in the soil to some degree by the end of the growing season. We have accumulated in the last several years a wealth of data on herbicide fate and behavior in the sandy region of central Minnesota to establish guidelines for proper use of these herbicides. Because of the slower rates of degradation in the cool northern climate, judicious management of herbicide applications is essential to maintain environmental quality.

E. Title of Objective: Develop computer models for BMPs that consider movement of water, nitrogen, and herbicides.

E.1. Activity: Mode of deposition of Minnesota Glacial Outwash soils and its influence on water flow.

E.1.a. Context within the project: Most of the models in the literature that deal with the transport of water and contaminants in soil assume a uniform movement of wetting front. These models include the CERES-Maize, SUBSTOR, and LEACHM that will be used in this study to assess the susceptibility of Minnesota Glacial Outwash soils to nitrate and herbicide leaching. Recently, it has been shown in the literature that there is a differential movement of water in sandy outwash soils. The focus of this objective is to identify soils where the wetting front movement is uniform and where there is differential wetting.

E.1.b. Methods: One soil in Minnesota Glacial outwash region with known mode of deposition of fine layers will be used to develop procedures for identifying soils with uniform and differential wetting characteristics. The site will be located at include the Staples Irrigation Center at Staples, MN. Wetting front characteristics will be studied at several antecedent moisture conditions. These moisture conditions will be created by irrigating a site with sprinkler irrigation overnight and then starting the wetting fronts studies at various stages of drying over the next two weeks. The position of heterogeneities will also be used to develop a simple model of predicting the position of the wetting front. Efforts will be made to merge this simple model with CERES-Maize, SUBSTOR, and LEACHM models to extend their applicability to soils where differential movement of water contaminants occurs.

E.1.c. Materials: Food dye, transducers, plastic sheets, computers, printer, flat bed image analyzer.

E.1.d. Budget: $50,000 **Balance:** $0

E.1.e. Timeline:

	7/93	1/94	6/94	1/95	6/95
Establish experimental plots	xxxx		xxxx		
Characterize water movement	xxxx		xxxx		
Develop model which considers the heterogeneity in wetting front				xxxx	
Incorporate into models					xxxx

E.1.f. Status: An evaluation of the potato growth/nitrate leaching simulation model SUBSTOR-Potato was conducted by comparing measured field data with simulated values for 1991 and 1992 (16 combinations of management and climate) in a sandy outwash soil (Verndale sandy loam - coarse loamy over sandy, mixed, frigid, Udic Argiborolls) of central Minnesota. The results of this work were summarized in the final report for an LCMR-funded project which ended in June 1993. In that study it was found that predicted yield, nitrogen (N) uptake, and nitrate-N leaching followed measured trends of increases with increased N application rate, however predicted values generally were not within one standard deviation of the measured data. Evaluation of irrigation management strategies using this model suggested that soil moisture depletions to about 40% of total water-holding capacity would result in higher yields and lower nitrate leaching compared to more frequent irrigation. Overall, these results show that the SUBSTOR model can predict relative trends in nitrate leaching, but needs further testing and validation before it can be adopted on a larger scale in Minnesota.

SUBSTOR-Potato, and most other mechanistic approaches to modeling solute transport, assume uniform infiltration across an area. Evaluation of such model predictions is complicated for situations where preferential transport is occurring. Preferential transport is situation where water infiltrates in only a few areas thereby bypassing a large fraction of the soil matrix. Preferential transport has been reported in sandy soils. Therefore we undertook the present study to evaluate the prevalence of preferential flow in the Verndale soil, and to determine if the occurrence of preferential flow could be related to depositional or pedogenic features observable in the soil. To do this we conducted a dye-tracing experiment using FD&C Blue #1 food dye. Experimental treatments included a combination of three initial soil water contents (WET, MEDIUM, and DRY) and three application rates (FLOOD, SPRINKLER-High, and SPRINKLER-Low) in an alfalfa field, plus two additional plots in an adjacent field with no history of alfalfa. We observed extensive preferential dye movement under FLOOD conditions, regardless of initial soil moisture or recent vegetation history. Preferential flow path (PFP) lengths resulting from the two SPRINKLER rates were much shorter. Within-plot variability was very high. The major initiators of PFPs were decayed roots, followed by the abruptness and topography of the boundary between the Ap and Bt horizons. Open burrows were not common, though they did cause extensive preferential flow in the two non-alfalfa plots. While the shorter PFPs observed with the sprinkler rates suggest that preferential flow is less important under unsaturated conditions, we caution that interpretation of dye traces must take into account variable dye retardation (relative to the wetting front) under different application rates, and due to variability in the amount of adsorption between horizons. In this study, dye traces discerned pathways and relative extent of preferential transport of this moderately sorbed chemical under the imposed treatments, but these dye pathways may not necessarily reflect patterns in movement of water or other chemicals.

The last part of this study was to evaluate the adsorption characteristics of the FD&C Blue #1 dye used in the field study. The specific objectives of this portion of our research were 1) to quantify the amount of equilibrium adsorption of FD&C Blue #1 food dye in the Ap, Bt, and C horizons of Verndale sandy loam ; and 2) to determine the relative amount of dye retardation compared to the wetting front under two different flow velocities, which approximate the FLOOD and SPRINKLER-High treatments in the field. Twenty four hour batch equilibration measurements resulted in values for the linearized Freundlich distribution coefficient (Kd) of 4.54, 25.59, and 4.32 L kg^{-1} for the Ap, Bt, and C horizons respectively. It was surprising to find greater adsorption in the subsoil (Bt) compared to the Ap horizon, it is often assumed that maximum adsorption will occur in the surface horizon which contains greater amounts of organic matter. Neither organic carbon nor clay content differences explained the variation. Experiments with repacked soil columns of each horizon showed that the dye is retarded relative to the wetting front, and that the extent of retardation depends on the flow velocity. In the Ap and C horizons about twice as much retardation was observed under unsaturated conditions (low flow velocity) compared to ponded conditions. Application rate had little effect on dye retardation in the Bt horizon - likely because the flow rate under ponded conditions was still very slow due to low hydraulic conductivity, thus allowing enough time to reach near-equilibrium conditions. Breakthrough curves of the dye and Br^- ion for the Ap soil showed that dye movement relative to Br^- ion is relatively slower at the lower flow velocity compared to ponded application. The occurrence of variable retardation as a function flow velocity has important implications for interpreting dye pathways as a surrogate of the pathways of water flow. In addition, knowing that there is increased adsorption in subsoil horizon(s) can further complicate the interpretation of dye patterns resulting from field experiments. Researchers using dyes as tracers of water movement need to consider these two factors when evaluating the results of studies that use dyes as tracers of water and solute movement. In conclusion, this study found that preferential transport does occur in this soil, especially if there is standing water at the soil surface.

E.2. Activity: Assessment of nitrate and herbicide leaching in Minnesota Glacial outwash soils.

E.2.a. Context within the project: Identification of best management practices that will minimize nitrate and herbicide leaching and characterization of soils according to the potential for leaching of agricultural chemicals require long-term (10-20 years covering several climatic cycles) data on crop yield, nutrient uptake and leaching of chemicals past the root zone for a whole series of management scenarios on various soil types. This type of information is currently not available for the Glacial Outwash soils of Minnesota. The cost involved for setting up experiments to gather this information would be prohibitive. One of the effective means of obtaining this type of data is through simulation models that integrate soil, climate, and management information to predict crop growth, availability, and movement of chemicals in the root zone. The focus of this objective will be to use validated models, along with the soil, climatic and current management practices data bases, to categorize soils as to their potential for nitrate and herbicide leaching and then, through simulations under various management scenarios, identify the best management practices that will minimize leaching. Currently, these models lack procedures to handle manure applied N. Based on the literature, sub models of manure mineralization will be added to the existing models.

E.2.b. Methods: The validated models will be used to generate crop yield and NO_3 and herbicide leaching under existing management practices for several soils in the Minnesota Glacial outwash area. The soils will be selected based on the area starting with the most dominant soil type.

The validated models will also be used to generate crop yield and NO_3 leaching vs. N input curves for various management scenarios. The N input rate, where the crop yield levels off and the NO_3 leaching increases dramatically, will characterize the best N input rate for a given management practice. The amount of N lost at best N input rate for a given management practice will be used to categorize the soil under consideration.

Various ratings of a soil will be compared to produce ranking of best management practices that minimize NO_3 leaching. Since NO_3 leaching for a given soil and management practice heavily depends upon the climate of the area, soil will be categorized at three probability levels (wet, average, dry) based on the climate of the area over the past 20-30 years.

E.2.c. Materials: Micro computer and printing peripherals.

E.2.d. Budget: $44,000 **Balance:** $0

E.2.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Continued validation of models	xxxxxxxx				
Risk characterization of soils		xxxxxxxxxxxxxxxxxx			
Summary and report					xxxx

E.2.f. Status: A series of studies quantified the role of major factors such as climate, soils, and fertilizer and irrigation management on water percolation and nitrate and herbicide leaching through outwash soils in Central Sands of Minnesota. Typically, soils in the Central Sands of Minnesota are developed from glacial outwash parent material. These soils have low production potential because of low soil fertility and lower capacity to hold water. Precipitation alone cannot sustain most agricultural crops during the growing season. Since ground water is shallow and easily accessible, extensive areas have been brought under cultivation since the 1960's by supplementing crop water needs with irrigation. Major crops of the area are corn and potato. These crops have often been fertilized excessively to maximize yield. Shallow surficial aquifers in the Central Sands of Minnesota are also the source of drinking water supply for most of the communities in the area. Contamination of the groundwater by nitrate and herbicides is primarily because the soils are nonadsorbing and have low water holding capacities, resulting in deep percolation of rain or irrigation water down the soil profile.

In the first study, we used a hydrologic water balance computer model to identify the peak leaching periods and the corresponding amount of percolation based on long-term daily meteorological data, and to compute the annual excess precipitation and irrigation that may percolate through Minnesota outwash soils with various water holding capacities. As expected, result of this modeling showed that the percolation losses decrease with an increase in soil water holding capacity. The occurrence of percolation losses in this region is highest during spring and fall because of a limited loss of water by evapotranspiration.

Since soils and climatic factors cannot be easily manipulated, the only viable option available to minimize nitrate leaching from these soils is through the management of irrigation and fertilizer and herbicide application. In the next study, we tested and validated the CERES-Maize model under the soil and climatic conditions of the Central Sands of Minnesota, and then identify the management practices that can minimize nitrate leaching. The validation was done against the experimental data on corn yield, N uptake and N leaching for four fertilizer application rates and two irrigation schedules on Verndale sandy loam soil (coarse loamy over sandy, mixed, frigid, Udic Argiboroll) during 1991 and 1992 at Staples, MN. In general, simulated values were close to the observed data. Simulation with 31 years of climatic data showed that N leaching in these soils was mainly caused by excess irrigation or unexpected rains that may occur right after irrigation. Therefore in order to minimize N leaching, irrigation should be applied so that there was always some unfilled porespace in soil to capture the unforeseen rain that may occur after irrigation.

The simulation results also showed that for outwash soils of Minnesota, using yield goal to select N application rates is not appropriate because climate is a major determinant of the yield in the area. Also, the irrigation trigger of about 30-40% and fertilizer application of about 180 kg ha^{-1} are sufficient for achieving maximum corn yield. Irrigation trigger for potato production may be higher because potatoes are more sensitive to water deficit stress. We also developed a procedure to characterizes the risk potential of these soils to N leaching based on the output results of long-term simulation of CERES-Maize. The procedure identifies fertilizer and irrigation management practices best suited for maximum yield and minimum N leaching for a given soil and climatic condition.

Although the rates of herbicide applications must adhere to label specifications, thus less variable, their fate in the field is subject to soil management practices, especially when irrigation is used to supplement moisture for crop production. Water management is, therefore, critical to proper herbicide use under field conditions. The patterns of movement of metribuzin and metolachlor observed in the Verndale soil under field conditions are similar to those simulated by the CMLS (Chemical Movement in Layered Soil) Model for both the Verndale soil at Staples and the Hubbard soil at Becker, MN.

In the next two studies, we conducted a field and simulation studies to evaluate whether or not subsurface drip irrigation is a possible alternative in providing substantial unfilled pore space to hold water from unforeseen rains that might occur right after irrigation. The field experiment consisted of measuring hourly soil water content profiles with Time Domain Reflectometry (TDR) probes under growing potato plants in both sprinkler and drip irrigated plots in the Verndale soil at Staples, MN. Wetting and drying patterns showed that there was little water movement to the upper parts of the ridge in the drip irrigated plot. Under both furrow and just below the center of the ridge, there was a large change in water content during the full canopy period. This large change in soil water content under the furrow was due to a greater amount of infiltration as a result of water runoff from the ridge. Large changes in soil water content just below the ridge was due to more water reaching the base of the plant from stem flow and then most likely from preferential water transport through cracks created by the expanding tubers. Small changes in water contents just below the shoulder of the ridge compared to just below the furrow were due to higher runoff from the shoulder of the ridge and thus less water infiltration.

Experimental results suggested that water movement in the soil profile under a ridge-furrow system is a two-dimensional process. Since the experimental characterization of water movement in the soil profile under a ridge-furrow system for a whole range of treatments is expensive and time consuming, we used a mechanistic 2-dimensional model (SWMS_2D) to evaluate the role of stem flow, and the depth of drip placement on percolation losses in subsurface drip irrigation treatments. Using the SWMS_2D model, we also quantified the differences in percolation between the sprinkler and drip irrigated plots.

Simulation results showed that there was little water movement towards the upper part of the ridge when the drip was installed at 40 cm depth or deeper from the top of the ridge in the Verndale soil. This observation has important implications if drip irrigation is also used for application of fertilizer. Since the potato roots are not fully developed at the early stages of potato growth, the simulation results suggest that surface application of starter fertilizer would be better than the application of fertilizer through the drip line. Deeper placement of drip led to excess percolation due to higher hydraulic conductivity of C horizon whereas shallow placement potentially present problems of drip tape being ripped during potato harvest. Simulation results also showed that irrigation water applied through the buried drip could reduce the water percolation losses significantly compared to sprinkler irrigation method if a rain comes shortly after the irrigation.

E.3. Activity: Determine soil conditional probabilities for percolation on north-central Minnesota sandy soils. Field measurements and modeling to determine soil temperature and soil moisture.

E.3.a. Context within the project: Both water quality and sustainability issues can be addressed by implementing more precise production management practice strategies on the sandy soils of central Minnesota, particularly with respect to irrigation, nitrogen, and herbicide applications for potato and corn. Among the obstacles limiting implementation of such strategies is a lack of knowledge about highly variable climate and soil conditions which govern the utilization and efficiency of these three production inputs (water, fertilizer, and herbicides).

E.3.b. Methods: Soil temperature and moisture models will be tested against field measurements to determine their relative accuracies on the sandy soil types of central Minnesota. Once tested and calibrated, these models will be used to calculate field working day probability functions for both the spring and the fall seasons. Using the state climate data base, a spatial analysis of field working day probabilities will be done.

E.3.c. Materials: Nearly 40 climate stations are available for the central sand plains region of the state. Station measurement histories vary from 50 to 100 years, but are deemed sufficient to characterize both the spatial and temporal variability of important climatic and soil conditions. One or two additional stations may be purchased to monitor conditions where field experiments will be done on objectives B, C, and D.

E.3.d. Budget: $41,000 **Balance:** $0

E.3.e. Timeline:	7/93 1/94 6/94 1/95 6/95
Inventory historical climatic data base	xxxxxxxxxxx
Field measurements	xxxxxxxxxxxxxxxxxxxx
Test models for temperature and moisture	xxxxxxxxxxxxxxxxxxxx
Compute probability distributions	xxxxxxxxxxxxxxxxxxxx
Evaluate applicability of probabilities and spray occasions	xxxxxxxxxxxxxxxxx

E.3.f. Status: Historical climatic distributions for six locations in the north-central region of Minnesota show some degree of spatial variability, primarily due to latitudinal position since the region stretches approximately 150 miles from south to north. The temporal, or year to year variability is much greater than the spatial variability. Extreme events such as very short growing seasons, 100 degree temperatures and 4 inch rainfalls generally occur less than five percent of the time and cannot be mediated by existing management practices anyway.

The only location with a soil temperature record of any length was Staples Irrigation Center (1983-1993). The temporal pattern in both the four inch and eight inch depth shows considerable variability in the early spring and fall periods, with lesser variability during the summer months. Average temperatures at a depth of four inches reach 50 degrees F or greater during the last week of April. This is sufficient to trigger more active mineralization rates from nitrogen sources in the soil and also indicates that crops sown in mid to late April should adequately germinate. The degree to which soil temperatures are moderated by irrigation is unknown on these soils, but may be useful to investigate in order to fine-tune site specific management of fertilizer and manure applications which supply nitrogen sources subject to mineralization rates highly regulated by a variable soil environment.

Soil moisture retention in the north-central sands is generally poor, especially in the near surface layers. Volumetric field capacity for soil moisture in many of these sands ranges from 15 to 18 percent, while volumetric wilting point moisture content ranges from 6 to 8 percent. This equates to an available water holding capacity ranging from 1.0 to 1.3 inches per foot of soil. A soil moisture submodel from CERES-Maize (1985), available through the Midwest Climate Center, was run on a composite climatic data set (using multiple stations) for north-central Minnesota covering the period from 1951-1993. The resulting temporal distribution of soil moisture in the region showed that beginning in mid July and lasting well into September, soil moisture levels in the top 60 inches are at their lowest levels, commonly less than half of available water holding capacity. In fact over a quarter of the time during late July and early August, available soil moisture values are less than 20 percent. This corresponds to the peak irrigation season for most crops in the region when rainfed soil moisture is supplemented heavily by overhead sprinkler applications.

Many irrigators in the north central sands use estimates of potential evapotranspiration on a daily basis coupled with monitoring soil moisture levels to help schedule irrigations during the crop season. However, little use is made of historical patterns of potential evapotranspiration and temporal soil moisture probabilities to critically look at irrigation design capacities. In addition, weather forecast probabilities are under-utilized in making decisions about when to apply irrigation as well as how much to apply. Probability of precipitation forecasts (POPs) and quantified precipitation forecasts (QPF) are available daily from the National Weather Service Forecast Offices in Minnesota, but are rarely used in irrigation decisions. Utilizing these information resources more fully should improve site-specific management of irrigation systems on the soils of north-central Minnesota. A pilot effort with some members of the North-Central Irrigators Association has been initiated to test this hypothesis.

Probability distributions for precipitation at the six climatic locations in the region, show that there is a twenty five percent chance of receiving 1.5 to 2.0 inches of excess (above average) rainfall during the months of June, July and August, the peak irrigation season. During the same period, there is a twenty five percent chance of having a rainfall deficit of 1.0 to 1.5 inches for any individual month. Frequencies for heavier one day rainfall events (0.5, 1, 2, and 3 inch quantities) were computed for the same set of climatic stations. They showed that on the average there are 5-6 one inch rainfall events per growing season, most of which occur in June, July and August. There are however a number of one inch or greater rainfall events which occur in May and September with a frequency of every two years, while similar heavy rainfalls in April and October occur with a frequency of about one year in three. These type of rainfalls may contribute more to leaching and runoff losses of nitrogen in the soil profile due to the absence of crop canopy that is more typical of these months. Best Management Practices (BMPs) for nitrogen in this area of the state already call for split applications to correspond more closely to crop need and uptake. This strategy alone can help compensate for the higher risk of leaching losses during these months. Precipitation events of 3 inches or greater occur across the region with a frequency of every 4-5 years and produce significant leaching losses regardless of the time of year.

Mechanical, cultural and chemical forms of weed control are used in the north-central region. The use of postemergence herbicides has been increasing in recent years, as producers have sought more flexibility in controlling weeds with a combination of methods. Late spring or early summer weed flushes missed by soil applied herbicides, cultivations or rotary hoes are often treated with specific postemergence compounds. Environmental conditions shortly before, during and after herbicide applications govern the efficacy of the compound in most cases as few herbicides are weather proof.

Spackman's method (1983) of defining spraying-occasions for herbicides was used to evaluate which of several environmental criteria were the most restrictive with respect to the use of postemergence compounds in the north-central region. Wind speed was by far the most restrictive climatic element in limiting spraying-occasions. The two wind criteria used for selecting spraying occasions were speeds less than 10 mph and speeds less than 5 mph, both of which are commonly recommended by agronomists or cited on label instructions. Using the hourly climatic records from Staples in 1994, the number of spraying occasions suitable for the use of postemergence herbicides from late May to late June were calculated. The number of spraying occasions which met the 10 mph wind speed criteria were six times more than the number which met the 5 mph criteria. This suggests opportunities to use any compounds which impose a risk associated with spray droplet or vapor drift are far fewer than for those which pose no such risk.

There are many opportunities to more fully utilize historical climatic data, soil moisture models, potential evapotranspiration estimates, weather forecast probabilities, and spraying occasion calculations in crop production management within the north-central region. Combined with greater utilization of soils maps and irrigation technologies, these information sources should be tested to evaluate their impact on site-specific management of irrigation water, nutrients and herbicides.

E.4. Activity: To establish a dialogue between soil scientists and potato producers through the information generated by a computer simulation model.

E.4.a. Context within the project: Maximum yield is safely achieved with excess irrigation and nitrogen fertilization; a practice which may entail the risk of nitrate leaching. There is always a risk of yield deficit when unforeseen climatic events turn optimal management into suboptimal water and N input. Risks associated with optimal agricultural managerial decisions will have to be fully appreciated by potato producers before they willingly "take that risk". Simulation models can predict yield and nitrate pollution for various managerial decisions and climatic events; thus providing a tool with which producers and soil scientists can select acceptable managerial risks.

E.4.b. Methods: Two potato fields will be selected from growers and/or the Anoka Sand Plain Water Quality Demonstration Project and/or the RD Offutt Company, Park Rapids MN. Simulation will be performed by the model NCSWAP. Simulated information will be used to discuss risks assumed and taken during the growing season; and to establish the advisability of using the computer simulation model as a managerial tool. Potato sap nitrate tests will be performed during the growing season. They will be correlated with actual and simulated data in order to establish the potential of this test to help growers in their managerial decision.

E.4.c. Materials: Electronic mail and/or FAX services will be needed between the St. Paul campus and the potato grower site. A portable high performance computer will be needed.

E.4.d. Budget: $16,500 **Balance:** $0

E.4.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Obtain initial field conditions	xxxx				
Simulation/dialogue		xxxxxx		xxxx	
Preliminary evaluation		xxxxxxxx			
Evaluation				xxxx	

E.4.f. Status: Computer simulation modelling was used to predict the nitrogen mass balance of the soil, water, and plant environment on a potato farm in Becker, MN. The model (NCSWAP) accurately forecasted a period of plant nitrogen stress during the 1994 season, and demonstrated how paradoxically there could be an increase in nitrate leaching. One outcome of this research is a recommendation for better irrigation practices, and higher crediting of field nitrogen sources.

NCSWAP operated in a real-time environment during the two growing seasons that farm nitrogen practices were analyzed. Climatic data and management decisions were updated continuously, and the feedback loop between grower and simulation was short. Off-season the model was validated using field data, and where needed, assumptions were modified. For instance, the model tended to overstate nitrate leaching, and this process was revised.

The model NCSWAP is a useful tool for field nitrogen management, and the mass balance approach also has potential as a teaching aid. The model can quickly and repeatedly test alternative nitrogen strategies, while demonstrating the relationship between various nitrogen sources and crop development. Application of this technology to site specific farming, however, is hampered by the models heavy data requirements.

F. Title of objective: Disseminate information.

F.1. Activity: Develop a network of on-farm demonstrations to serve as the core for the educational effort.

F.1.a. Context with the project: One of the most effective methods for disseminating management information to farmers is quality, local, on-farm demonstrations.

F.1.b Methods: The core of this educational program is five strategically placed on-farm demonstrations of tillage and fertilizer or manure management strategies to reduce and/or make more efficient use of nitrogen for corn, alfalfa or potato. Plots will be large to accommodate and simulate cooperators' operations and designed in a randomized complete block or split plot design with three replications. Treatments and crop responses will be characterized in enough detail to determine probable cause and effect on yield differences and inputs tallied to assess influences on profitability. Data collected from growers' fields on nitrate movement will be used to allow comparison of how management practices affect nitrate losses and crop production.

Nitrate-N will be determined in soil and water samples collected at various depths through the growing season at two demonstration sites. Field days will be scheduled at each demonstration site.

F.1.c. Materials: Materials necessary to accomplish this activity will consist of: I) farm equipment, seed, fertilizer/manure supplied by farmer cooperators; II) suction tubes, sample bottles and bags, use of existing assorted laboratory equipment for analyzing soil, water, plant tissue and manure samples; III) scales for determining manure application rates, data forms, field markers, tape measure, other plot related miscellany, fact sheets, field maps and advertising flyers.

F.1.d. Budget: $45,000 **Balance:** $0

F.1.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Identify cooperators	xxxx				
Assess farming operation and design demonstration	xxxx				
Implement demonstrations and collect data			xxxx		xxxx
Field tours held in cooperation with local agency advisors			xxxx		xxxx

F.1.f. Status: Five on-farm demonstrations of efficient nitrogen and manure management were held in the north central sands region. Three demonstrations focused on manure management (two in corn and one in edible beans). A fourth demonstration looked at refining split applications of nitrogen in potato. The fifth demonstration looked at deep tillage and N source in a soil with a compacted Bt layer.

The manure demonstrations proved to be a good learning tool both for the growers and the support staff. Manure application rates were substantially reduced through the process of manure testing and spreader calibration.

The complexity of the manure issue was highlighted in this project. By doing the demonstrations on-farm, a whole-farm component is automatically introduced into each management practice being demonstrated. The Myron Quaal farm and the Marvin Runyan farm, although they are both dairies and only ten miles apart on sandy soils, provided very different responses to recommended manure management. This was primarily due to differing attitudes toward the value of corn and how the crop fits in their farm structure. The Tobkin edible bean manure demonstration again showed that the manure issue must be addressed within a whole-farm perspective. Refining manure application rates may be of secondary importance when compared to the potential for the manure to improve bean root health.

Overall, the manure demonstrations provided good local examples of refined manure management practices. There is strong interest in these communities to use this information to save money on fertilizer where manure is already being spread. The demonstrations showed that manure can be a dependable, environmentally sound sole source of nitrogen when combined with lab analysis and spreader calibration.

The John Moyer potato nitrogen demonstration showed that John was able to achieve higher yields and reduced nitrate leaching by reducing nitrogen rates in the starter and timing his late applications with the use of the petiole sap nitrate test.

The John Moyer deep tillage and nitrogen source demonstration suggested that the deep tillage improved rooting depth two years after the tillage was performed. There was no evidence that deep tillage increased nitrate leaching potential.

F.2. Activity: Produce demonstration data summaries and conduct workshops for farmers and field staff of local agencies.

F.2.a. Context within the project: Information from the on-farm demonstrations and other project objectives will be summarized to allow growers to compare how their practices affect nitrate movement and production and to encourage adoption of new guidelines that will decrease losses of nitrate nitrogen while maintaining profitable farming operations. Joint training of field staff of the Minnesota Extension Service, the Soil Conservation Service, and Soil and Water Conservation Districts will greatly multiply the information dissemination efforts by using "in place" agency field staff as vehicles for information transfer.

F.2.b. Methods: All cooperators, including farmers, will meet to evaluate the data collected and to determine the program for farmer and field staff workshops. Decisions on number and location of the programs will be made at that time. Presentations from both farmer cooperators and researchers will be included. Data from the demonstrations and other research components will be summarized into workshop presentation materials and fact sheets for general distribution in the North-Central Sands area.

F.2.c. Materials: Audio/visual aids and printed materials.

F.2.d. Budget: $10,000 **Balance:** $0

F.2.e. Timeline:	7/93	1/94	6/94	1/95	6/95
Prepare data summaries	xxxx		xxxx		
Field staff training	xxxx		xxxx		
Farmer training workshops	xxxx		xxxxxxxxx		

F.2.f. Status: Data summaries for all the demonstrations have been completed and reviewed with the farmer cooperators and support staff. Further meetings are in progress to expand the manure issue to the level of soil quality/health.

V. Evaluation: Each individual objective will be evaluated on how well each achieved specific research and educational goals. Evaluation of the overall project will be obtained by feed back from field staff as to the amount of changes in farmer practices which could affect the extent of contamination of ground water by agricultural chemicals.

VI. Context within Field: Quantitative field measurement of nitrate and herbicide movement through soil is very expensive and difficult. For this reason there is paucity of data in this area of research. This project will provide critical data dealing with agricultural chemical use on irrigated sandy soils overlaying surficial aquifers. The computer modeling component will provide an opportunity for interpolation to many soil\climate circumstances which will have application over parts of four states in the upper Midwest.

VII. Benefits: The most valuable benefit to Minnesota is the potential reduction of agricultural chemicals from loss to groundwater.

VIII. Dissemination: This project has an objective devoted entirely to technology transfer and information dissemination. In place field based staff of the Minnesota Extension Service, the Soil Conservation Service, Soil and Water Conservation Districts, and the Minnesota Department of Agriculture will be responsible for information dissemination with participation from state based staff.

IX. Time: This information generated from this project will be limited by its one biennium time frame but nevertheless should yield useful data.

X. Cooperation: Cooperators will include eight faculty at the University of Minnesota, five specialists at the Minnesota Department of Agriculture, six county Extension agents, the Staples Area Technical College Irrigation Center, R.D. Offutt Co., and the Irrigators Association of Minnesota.
The activities under this project will be coordinated with those under several on-going projects of similar nature. However, this project has several unique variables not addressed by other projects. There have been very few previous research efforts in Minnesota related to nitrogen fate and movement in soil under potato production. Other states such as Wisconsin have conducted nitrogen-related research on irrigated potatoes and these results have been used to help formulate the treatments proposed in the present project. Two other projects are also being conducted in the sand plains area. Several Soil Science faculty members are participating in these projects. The Anoka Sand Plain demonstration project is based on current knowledge of best management practices, not on potential improvements of these practices. For a high value crop such as potato, untested changes in production could lead to substantial monetary losses. Therefore, changes in nitrogen management practices have to be studied on a small scale before they can be recommended to growers. The Management Systems Evaluation Area (MSEA) project has been set up to quantify losses of nitrate in a defined system, with emphasis on fertilizer use and corn production, but does not address nitrogen management practices or diagnostic techniques to help reduce these losses. Coordination with the Pineland Clean Water Partnership Project conducted in the Park Rapids area will also be undertaken. Preliminary discussions with Pineland project leaders including cooperating scientists from the U.S. Geological Survey have already been completed. The demonstration component will be incorporated into several existing programs: the Anoka Sand Plains Project, the SCS-Extension Nutrient Management/Conservation Tillage Program, and the Pineland Clean Water Project.

Note: Those cooperators listed that do not have a time commitment are being used as consultants only and will not be responsible for status reports.

A. **Dr. H.H. Cheng**, Soil Chemist, Soil Science Department, UM, will be the principal investigator on the herbicide leaching evaluation. Two year time commitment - 10%. Dr. Cheng is project manager for the two year duration - 5% time; He will also coordinate activities described in Objective D over the two year duration of the project - 5% time.
B. **Dr. Satish C. Gupta**, Soil Physicist, Soil Science Department, UM, will provide leadership in the water flow modeling and field validation effort. Two year time commitment - 5%. Dr. Gupta will contribute to Objective E1 and E2 over the two year duration of the project - 5% time.
C. **Dr. Jean A.E. Molina**, Soil Microbiologist, Soil Science Department, UM, will provide advice on the N transformation dimension of several objectives and have primary responsibility for the computer modeling efforts. Two year time commitment - 5%. Dr. Molina will contribute to objective E4 over the two year duration of the project - 5% time.
D. **Dr. John F. Moncrief**, Extension Soil Scientist, Soil Science Department, UM, will advise on the field demonstrations and provide leadership in the corn-N source evaluation. Two year time commitment - 5%. Dr. Moncrief will contribute to Objective C2 over the two year duration of the project - 5% time.
E. **Dr. Clive F. Reece**, Soil Atmospheric Physicist, Soil Science Department, UM, will provide leadership in the water flow modeling and field validation effort addressing stem and canopy flow of water and contaminants. Two year time commitment - 10%. Dr. Reece will contribute to objective C1 during the two year duration of the project - 10% time.
F. **Dr. Carl J. Rosen**, Extension Soil Scientist, Soil Science Department, UM, will advise on the field demonstrations and provide leadership in the potato-N management phase. Two year time commitment - 12.5%. Dr. Rosen will contribute to the coordination of Objectives B (5% time) and C1 (5% time) and will assist in supervising field operations in objective D (2.5% time) over the two year duration of the project.
G. **Dr. Mark W. Seeley**, Extension Climatologist, Soil Science Department, UM, will provide leadership on the climatic influences on conditional probabilities for field working days and leaching losses of contaminants. Two year time commitment - 6%. Dr. Seeley will contribute to objectives E2 (2% time) and E3 (4% time) over the two year duration of this project.
H. **Mr. Jerry A. Wright**, Extension Agricultural Engineer, will provide expertise on the irrigation scheduling dimension of modeling and field validation.
I. **Mr. Bruce R. Montgomery**, Special Projects Coordinator, Minnesota Department of Agriculture, will have primary responsibility for the farming practices survey. Two year time commitment - 4%. Mr. Montgomery will coordinate and administer objective A over the two year duration of the project - 4% time.
J. **Mr. Doug J. Gunnink**, On-farm project coordinator, Minnesota Department of Agriculture, will have primary responsibility for coordination of the "farmer cooperator" demonstrations. Two year time commitment - 20% Mr. Gunnink will be responsible for coordinating the demonstration projects in Objective F over the two year duration of the project - 20% time.
K. **Dr. Mary J. Hanks**, Supervisor, Energy and Sustainable Agriculture Program, Minnesota Department of Agriculture, will have primary responsibility for supervision of the "farmer cooperator" demonstrations. Two year time commitment - 2.5% time. Dr. Hanks will contribute to review and supervision of the demonstrations described in Objective F over the two year duration of the project - 2.5% time.
L. **Mr. Norman J. Krause**, Executive Director of the Irrigators Association of Minnesota, will be providing input for potential survey respondents and farming relevance of research goals.
M. **Mr. Dale Steevens**, Agronomist, R.D. Offutt Co., will cooperate on field evaluation of irrigated potatoes for N management and irrigation scheduling research objectives.
N. **Mr. Mel Wiens**, Senior Plot Coordinator, Ag. Exp. Sta., UM will supervise treatment establishment and data collection at the Staples Irrigation Center.
O. **Ms. L. Axton, Mr. D. Cooper, Mr. T. Hovde, Mr. R. Stauffer, Mr. L. Williams, and Mr. W. Yliniemi** Minnesota Extension Service, will coordinate the educational activities in their respective counties.

XI. Reporting Requirements: Semiannual status reports will be submitted not later than Jan. 1, 1994, July 1, 1994, Jan. 1, 1995 and a final status report by June 30, 1995.