July 1, 1993

LCMR Final Status Report - Summary - Research

I. Development of Aspen Decay Models for Mature Aspen Stands - Forestry 21

Program Manager: Dennis Hummitzsch, Land Commissioner
Koochiching County Land Department
International Falls, MN
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A. M.L. 91 Ch.254, Art. 1 Sec.14 Subd: 7.g Appropriation: $85,000
Balance: $0

Aspen Decay Models for Mature Aspen Stands: This appropriation is to the commissioner of natural resources to contract with Koochiching county and the University of Minnesota, College of Natural Resources, to develop models for aspen decay in mature aspen stands.

B. Compatible Data: Not applicable

C. Match Requirement: Not applicable

II. Narrative

The amount of aspen timber volume which is lost to decay is assumed to be large in Minnesota. Forest managers need more information on managing mature aspen stands so that this loss is minimized. By understanding the relationship between individual-stem decay and stand characteristics, decisions can be made as to which mature stands should be harvested first, which can be left, and how long stands can be left before the decay loss is critical. The accuracy of long-range planning efforts can be increased by incorporating this new information into existing growth and yield models. Given the increasing pressure on Minnesota's aspen resource, accurate long-term planning and forecasting is critical. This new information will also be developed in the form of indices which classify stands as to their vulnerability to decay (risk-level) based on stand characteristics such as soil type, site index, and age. These indices could be easily placed into existing geographic information systems to serve as an aid for site specific harvesting operations.

III. Objectives

A. Develop and implement a sample design (survey) to obtain data relating Aspen decay and stand characteristics.

A.1. Narrative: While relationships between inner-stem decay and outer-stem characteristics are well documented, the relationship to stand-level characteristics such as soil type, site index, and age is still vague. An effective survey will be developed in cooperation with the Minnesota DNR and other researchers in the field.

A.2. Procedures:

A key to the success of this project is obtaining data from a broad cross-section of stand conditions in Northern Minnesota and other similar locales. In addition to being prohibitively expensive, collecting all "new" data is unnecessary. Data for this project may come from two sources:

1. Previous studies of aspen decay having the necessary variables. These studies may or may not have looked at relationships between decay and stand characteristics but could be used for this purpose.

There are a number of previous studies of aspen decay in Minnesota, Ontario, and Alberta, as well as elsewhere. Several sources of data have already been identified. The Minnesota Department of Natural Resources recently conducted an aspen decay project (A. Jones and O. Phillips, Minnesota DNR Aspen Loss Assessment Work Plan, 1989). While this project did not specifically look at the question of how aspen decay relates to stand characteristics it does provide some of the data necessary to look at that question.

A study conducted by the Ontario Ministry of Natural Resources in northwestern Ontario also provides appropriate data (R. Miller, et. al., Ontario Ministry of Natural Resources 1990, Proposed Methodology Enhancements of Trembling Aspen Soil Site/Productivity Relationships in Northwestern Ontario). This study involved remeasuring a large number of permanent plots and felling a number of associated trees for stem analysis.

Initial conversations with these two projects indicate that we will most likely be able to use the data from these projects in this study and effectively increase our sample size. This in turn will result in a larger regional applicability to any relationships which we can model.

In addition to these two recent efforts, there are also a number of older studies which may prove useful:

Maier, G.B. and D. Darrah. 1972. Decay levels in mature aspen stands, Whitecourt, Alberta, Canada. Alberta Forest Resource Development Agreement Project no. 1467-72. 376 pp.

Schmitz, H. and L. W. R. Jackson. 1927. Heart rot of aspen with special reference to forest management in Minnesota. University of Minnesota Agricultural Experiment Station Technical Bulletin 50. 43 pp.

Morawski, Z. J. R., J. T. Basham, and K. B. Turner. 1958. Survey of pathological condition in the forests of Ontario. Ontario Department of Lands and Forests, Division of Timber, Report no. 25 (co-studies) 96 pp.

Gevorkiantz, S. R. and W. A. Duerr. 1938. Methods of predicting growth of forest stands in the forest survey of the Lake States. USDA Forest Service, Lake States Forest Experiment Station, Economic Notes no. 9. 59 pp.

As much useful data as possible will be assembled from reports and historical records.

2. Field data collected specifically for this project.

This data source will certainly be the bulk of the data for this project. A number of factors need to be considered in order to collect useful data. Plots will be established in either the aspen-birch unit or northern pine unit of the statewide (Phase I) inventory in order to overlap measurements of this inventory taken in 1988-1990 and at earlier inventories. The primary emphasis will be in Koochiching and St. Louis counties because of the large acreage in mature aspen stands found in this county.

Using the phase II forest management inventory state and county lands in the area, potential stands for data collection will be located that are 1)in the Aspen cover type, 2)within one mile of a road, 3)between the ages of 20 and 80, and 4)have a site index greater than 40.

Critical to the success of the study is sampling stands over a wide range of age, site index, and tree size. Therefore, the following matrix of site quality versus stand age will be sampled as completely as possible (it is expected that tree size will be broadly distributed by sampling from this matrix):

Stand Age	Site Index			
	40 - 60	60 - 70	70 - 80	80+
21 - 30	4+ plots	4+ plots	4+ plots	4+ plots
31 - 40	4+ plots	4+ plots	4+ plots	4+ plots
41 - 50	4+ plots	4+ plots	4+ plots	4+ plots
51 - 60	4+ plots	4+ plots	4+ plots	4+ plots
61 - 70	4+ plots	4+ plots	4+ plots	4+ plots
71+	4+ plots	4+ plots	4+ plots	4+ plots
Total	24+	24+	24+	24+

Our goal will be to have a minimum of four field plots in each cell. Where some cells can be completed with data from previous studies we may collect less field data. One plot will be considered one observation in the cell of the above mentioned matrix. To save on travel costs and be more effective in the field, these plots may be clustered within stands or within locales.

Each plot will consist of nested 1/15th (30.4 feet radius) acre and 1/100 acre fixed radius plots. All trees larger than 5" will be tallied on the 1/15th acre plot and trees greater than 1" but less than 5" will be tallied on the smaller plot. On each plot, all trees >1" diameter at breast height will be measured for species, diameter, total height, height to live crown base, and indicators of decay problems will be noted. In addition, degree of closure of the crown canopy, aspect, slope, observation of recent disturbance, site quality, and soil type will be recorded for each plot. Site index will also be calculated for each plot based on the height and age of three dominant/codominant trees located on or near the plot. Where appropriate, these site trees will also provide an estimate of stand age.

Alternatively, available records may provide a good estimate of age. Measurement and coding of stand variables will be consistent with the existing Phase I permanent plot system.

Following measurement of the plot, four trees will be selected randomly within the available diameter classes from each plot. These trees will be felled at 0.5-foot stump height and sectioned at breast height (4.5 feet) and at 4-foot intervals thereafter to the tip. After felling, total tree length and length of live crown will be measured. Each section will be inspected for the presence of conks, cankers, borer activity and decay. The location of each of those on each section will be recorded with an appropriate symbol on a map of each 4-foot section. Species of conks and causal agents of cankers will be identified using macroscopic characteristics. The width of conks at their widest point and the length of cankers will be recorded.

The cross-sectional face of each section will then be examined for the presence of decay. Three stages of decay will be distinguished; incipient, intermediate and final. Incipient decay will consist of wood that is faintly colored from a light pink to straw brown. The intermediate stage includes all degrees of coloration from straw to brown but wood is apparently still hard and firm. Final stage includes all soft, punky wood (or missing wood) irrespective of color.

The area of each cross-section which is solid or decayed will be determined by one of methods. The first will involve placing a transparent grid over the stem cross-section. Boundaries of the stem and each stage of decay will be traced onto the grid. This grid will then be planimetered or digitized in the office to arrive at estimates of the amount of decay and sound wood in the cross-section. The second possible method will involve photographing each cross section in a standard fashion so that the photographs could then be planimetered or digitized as above (This technique has been used with success before - Goelz, J.C.G. and T.E. Burk. 1987. Testing a photographic method for measuring stem cross-sections. Forest Science 33(3):784-89). The choice of method will be made after additional review.

The areas in decay and sound wood will be converted to volumes via standard mensurational formulas (e.g., smallans volume formula for the majority of the bole, cylindrical and conic volume formulas at the base and tip, respectively)

Finally, each plot will be located on a map or existing aerial photography such that additional large-scale photography can be obtained at a later date. This photography may be used to identify clonal differences within a plot and to provide additional stand variables that might typically be available to forest managers. To evaluate the efficacy of using aerial photography to identify clonal differences, bud or leaf samples will be collected from each tree on the plot. These will be subjected to protein analysis which can help to identify genotype (personal communication, Dr. Glenn Furnier, Univ. of Minnesota, Department of Forest Resources).

A.3. Budget

	LCMR Funds	Matching Funds
a. Amount Budgeted:	$50,000	$0
b. Balance:	$0	$0

The contract between the DNR, the University of Minnesota, and Koochiching county defines specific objectives which result in specific disbursements of dollars.
All tasks were completed and notice of this forwarded to the DNR who then arranged for payment.

A.4. Timeline for Products/Tasks — July91 Jan92 June92 Jan93 June93

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Historical/existing data acquisition  ------------|
Develop survey and field guidelines                --|
Field data collection                       |-----|
Aerial photo data collection                  |-|
Keypunching of field data                         |----|
Aerial photo interpretation                       |----|
Tissue analysis for clonal difference                    |--|
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A.5. Status:

Data have been obtained from several historical studies. Data from 83 aspen stands in Ontario have been obtained from the Ontario Ministry of Natural Resources. These data were collected from 1/10 acre fixed radius plots upon which all trees were felled and sectioned. The volume of healthy and decayed wood was calculated by graphing each tree in 2 dimensions (width, height). Assuming the tree cross-sections were round, these graphs were used to calculate the merchantable pulpwood) volume and the net ((of decay) merchantable pulpwood volume. These data were collected in the mid 1950's and are henceforth referred to as the Ontario Data. As an aside, several hundred more plots are available from stands classified as other forest types. At some point, the models developed in this study will be extended to the other forest types for Ontario.

Data were also obtained from a 1990 study conducted by the Minnesota DNR. However these data do not have the stand-level information necessary for this work.

The aspen data collected by the USFS FIA (Forest Inventory and Analysis) Project have also been obtained. FIA plots can be classified as full or partial measurements. Only the full measurement plots have any information on decay actually observed on the plot; this information being estimates of decay based on external stem indicators such as conks, cankers, and wounds. These full measurement FIA data are henceforth referred to as the FIA Data.

The data collected in the summers (July-Sept.) of 1991 and 1992 under this project consists of 53 plots located across Koochiching and St. Louis counties in Northern Minnesota. These data have all been keypunched and checked for errors. These data are henceforth referred to as the LCMR Data. A formal survey design and set of field guidelines were developed and used in completing the field work.

All data have been incorporated into a relational database management system to (a) facilitate analysis and (b) serve as a central storage base.

A.6. Benefits: In addition to providing information for objective B, objective A would provide valuable data for other, future efforts in characterizing forest growth, development, and yield. Some examples are individual stem volume and taper equations, and climate change impact analyses. This data would be maintained by the Great Lakes Forest Growth and Yield Cooperative located at the University of Minnesota and be made available to researchers upon request.

B. Develop relationships between aspen stem quality and forest stand characteristics

B.1. Narrative: Individual stem quality would be related to stand characteristics through various multivariate statistical analysis and modeling techniques.

B.2. Procedures:

Actual and Percent volume in sound wood, incipient, intermediate and final stages of decay will be developed for each tree that is felled and sectioned. Using appropriate expansion factors these values will be expanded to a per acre basis for each stand.

Multivariate analysis techniques will be used to relate exogenous variables such as average stand diameter, quadratic mean diameter of the stand, site index, average height, average crown ratio, percent crown closure, basal area, trees per acre, and other variables to the different endogenous variables including absolute and percent decay (each type) and various transformations. Initially, extensive use of graphing techniques will be made to identify appropriate relationships between these variables. As an example, a three-dimensional graphical analysis of final stage decay, site index and age will enable us to see if there is any 2 or 3 dimensional relationship between the three variables.

Model estimation will rely on linear and nonlinear regression, and may include principle component analysis. Principal component analysis may help to identify linear combinations of the variables that provide a more parsimonious description of the relationships.

A guiding criteria will be that any developed equations will facilitate the estimation of decay levels from commonly available stand characteristics or combinations thereof. In essence this will lead to a better understanding of the economic rotation age of aspen or equivalently, how long aspen can be held on the stump while minimizing wood fiber loss.

Further analysis will involve relating our conclusions about aspen decay to the aspen decay relationships found in both phase I and phase II Minnesota statewide inventories as well as in the continuous forest inventory of Koochiching county. By applying our equations to these surveys we will determine estimates of decay for a number of stands and then compare our estimates with those found in the survey. The results should provide more accurate decay estimates for these surveys.

Upon completion of the statistical analysis and modeling, the results will be incorporated into an existing growth and yield model and into the GIS system of Koochiching county. This will help facilitate the use of these results by integrating the information into a field usable format. GIS maps are used on a daily basis as well as for future planning. It will also serve as a model for other counties.

Results of the project will be presented at least once at an annual meeting of the Great Lakes Forest Growth and Yield Cooperative. The members of this Cooperative include local/state/federal/industry foresters and land managers. Within Minnesota, non-member local government officials (county land commissioners) will also be invited to the presentations. In addition, summary reports will be distributed to appropriate land commissioners within Minnesota.

B.3. Budget:

	LCMR Funds	Matching Funds
a. Amount Budgeted:	$35,000	$0
b. Balance:	$0	$0

The contract between the DNR, the University of Minnesota, and Koochiching county defines specific objectives which result in specific disbursements of dollars. All tasks were completed and notice of this forwarded to the DNR who arranged payment.

B.4. Timeline for Products/Tasks

Timeline for Products/Tasks	July91	Jan92	June92	Jan93	June93
- organize data		I-I	I-------I		
- graphical analysis		I----I			
- statistical analysis		I-------------------------I			
- computer programming of results into existing growth models				I---------I	
_ Integration of results into GIS				I-------I	
- presentation of results			I---I		I---I
- distribution of summary report					I-I

B.5. Status:

All of the data to be used in this project, historical data and that collected specifically for this project, have been combined into a relational database. Early in 1993, a preliminary report describing initial statistical analyses was provided to the Minnesota DNR for approval. Such approval was received and more detailed analyses followed.

Prior to beginning statistical analysis, many preliminary steps were taken to convert the variables observed on individual trees, i.e., diameter outside bark at breast height (D), tree height, crown length, etc., into variables useful from the context of modelling decay volume per acre or the percent of stand volume in decayed wood. To do this, a large number of intermediate computer programs were written and utilized. For the Ontario Data, these programs basically aggregated tree variables to a stand basis. As an example, the volume was recorded in the data for each tree based on stem analysis. These per tree merchantable pulpwood volumes were summed for each plot and the result multiplied by 10 (these were 1/10 acre plots) to obtain per acre merchantable pulpwood volumes, Similar aggregation was done for the FIA Data.

The LCMR data was more complicated as it involved felling and sectioning a large number of trees. These trees formed the heart of the information on decay and in order to eventually obtain the needed stand variables a number of auxiliary relationships were developed, including:

True Individual tree Volumes - The true volume for all felled trees in the LCMR Data was calculated by summing the volumes of all sampled sections. By summing the volume of individual sections and doing appropriate interpolations, the true volume from any lower point to any upper point on the bole could be obtained for all felled trees. A variety of merchantability limits were applied and true volume calculated for the volume from stump to top diameters outside bark of 2, 3, 4, and 5 inches. In addition the total stem volume was calculated.

Lower Stem Diameter Inside Bark Equations- Because of an oversight the first year, the diameter inside bark at breast height (d) was not always observed. Therefore the following functions were postulated and fitted to the data collected the second year of the study:

$$d = aD^{b} \qquad [1]$$

and

$$d = aD^{b}e^{c\ CROWN} \qquad [2]$$

where a,b, and c are coefficients to be estimated and CROWN is the ratio of live crown length to total stem length (commonly referred to as crown ratio). Equation [2] was used in this work but [1] was developed as other studies may not have information on crown length or ratio. In addition, while the diameter inside bark at stump height (d_s) was always observed, the stump height varied and an equation predicting diameter inside bark at a consistent stump height (1.0 feet in this study) was required. The equation was:

$$d_s = \left(\frac{d}{a\ d^{b}}\right) + (4.5 - h_s) \qquad [3]$$

where h_s = stump height. Equation [3] is derived assuming the shape of the geometric solid between stump and breast height is that of a neiloid. Equations [1]-[3] were with weighted nonlinear regression assuming that the variance was proportional to D^2. Coefficient estimates and fit statistics are provided in Table 1.

Individual Tree Volume and Height Equations - To obtain the volume of each tree which consisted of wood in intermediate and final stages of decay, the geometric volume formulae above (Smalians, neiloid, cylinder, cone) were used along with the observed cross-sectional area of decay at the top and bottom of each cut section. Then, as with the individual tree volumes, the volume in decayed wood was calculated for each felled tree by summing the volumes of appropriate sections and making proper interpolations. From this an average percent decay was developed as

$$\%d = \frac{decay\ volume}{total\ volume}$$

Because the sampled (felled) trees were sampled at random, the observed average percent decay can be directly extrapolated to be the observed average decay for the plot when expressed on a percent basis.

It was also necessary to determine the volume on the remaining (non-felled) trees on each plot. Therefore equations were developed to estimate total height, total volume, and merchantable volume. Such equations are available elsewhere but given the quality of these data, it was best to develop new ones. Because it is appropriate to estimate volume below breast height from basic mensurational formulae (i.e., a neiloid frustrum), the volume equations fitted here were for the volume from breast height to some top diameter (0 inches in the case of total volume above breast height). The total tree volume, including the volume below breast height can then be easily obtained by addition.

$$V_t = V_{bbh} + V_{abh,d_t}$$

Note that when d_t=0, V_t is equal to total tree volume. As with equations [1]-[3], above, a number of possible equations were examined with the following being the best when compared as to fit and predictive ability.

$$h_{abh} = b_1\left(1 - e^{-b_2 D}\right)^{b_3} SI^{b_4} \qquad [4]$$

$$V_{abh,0} = a\left(\frac{h_{abh}}{D}\right)^{b} D^2\ h_{abh} \qquad [5]$$

$$V_{abh,d_t} = V_{abh,0}\left(1 - a\left(\frac{d_t}{D}\right)^{b}\right) \qquad [6]$$

where h_{abh} is the height from breast height to the top of the tree and SI is site index. All other variables have been previously defined. The coefficients and fit statistics for equations [4]-[6] are also shown in Table 1. Using the above functions, the merchantable volume on each tree on each plot was estimated as the volume from a stump height of 1.0 foot to a d_t of 3.0 inches..

Table 1. Coefficient estimates and summary statistics for equations [1]-[6].

Equation Number	Sample Size	a	b	c	d	R^2	|e|
1	237	0.9427	0.9832	N/A	N/A	0.99	0.16
2	237	0.9342	0.9805	0.04907	N/A	0.99	0.04
3	237	0.000174	2.4925	N/A	N/A	0.95	0.48
4	157	12.4514	0.2273	1.6166	0.4273	0.82	3.49
5	483	0.001855	0.1083	N/A	N/A	0.95	1.32
6	1752	0.7636	3.9749	N/A	N/A	0.93	0.14

Other stand-level variables such as basal area per acre (BA, ft^2/acre), number of trees per acre (TPA), and quadratic mean diameter (QMD) were calculated as appropriate. Similar aggregation was done for the Ontario and FIA Data as well.

Following these preliminary steps, three data sets as described in Table 2 were available. A large number of additional variables, including observations of simple soil traits, average phenology (bark coloration, leaf size, etc.) were also available but preliminary analysis suggested that those variables in Table 2 were the most promising. .

Table 2. Description of LCMR, Ontario, and FIA data sets.

Variable	Data Set								
	LCMR			Ontario			FIA		
	min	mean (s.d.)	max	min	mean (s.d.)	max	min	mean (s.d.)	max
Decay (%)	0.9	10.5 (7.7)	34.0	0.8	15.7 (11.1)	54.0	0.0	7.2 (7.5)	41.3
Stand Age (years)	0.8	45.8 (12.3)	68.0	44.0	94.1 (30.5)	157.0	2.0	45.5 (21.0)	103.0
Site Index (ft)	54.4	72.3 (8.7)	94.8	24.7	37.8 (5.7)	50.1	24.0	66.8 (11.1)	91.0
Basal Area (ft^2/acre)	2.5	109.7 (46.2)	210.5	47.4	152.4 (44.0)	312.1	3.8	66.8 (36.8)	183.8
No. of Trees per Acre	15.0	262.6 (95.8)	480.0	130.0	304.5 (105.)	590.0	7.6	159.2 (90.8)	393.3
Quadratic Mean Diameter (Inches)	5.5	8.8 (2.0)	13.9	5.8	9.9 (2.0)	14.0	5.5	9.0 (1.8)	16.5
Average Crown Ratio	5.2	15.6 (5.3)	30.0	N/A	N/A	N/A	N/A	N/A	N/A

Initial analyses revealed that the FIA data did not contain any useful (in the context of modelling) relationships between %decay and any stand-level attributes. No statistically significant relationships could be found. This was to some extent anticipated due to the inherent nature of the FIA plot design. These plots are actually clusters of 10 small variable radius plots. This confounds the classification of the plot as to forest type, the determination of age and site index, and many otherwise useful stand level variables. Therefore the %decay models were developed with the LCMR and Ontario Data only.

Once the data described in Table 2 were assembled, the modelling of decay on a whole stand or per acre basis was begun. Two basic model formulations were desired,

Risk Index Model - The risk index model was formulated in the context of logistic regression and is meant to be used to rank stands as to their probable risk level to significant incidence of decay. A binary variable was developed having a value of 1 when the amount of decay exceeded 15% and a value of 0 when the amount of decay was less than 15%. Logistic regression was then used to fit the function:

$$Y_{0,1} = \frac{e^{a + b\left(\frac{SI}{QMD}\right)}}{1 + e^{a + b\left(\frac{SI}{QMD}\right)}} \qquad [7]$$

This model was fitted by minimizing the following loss function which provides maximum likelihood estimates of a and b:

$$\sum_{i=1}^{n} Y_{0,1} \log(\hat{Y}_{0,1}) + (1 - Y_{0,1}) \log(1 - \hat{Y}_{0,1})$$

In addition to SI/QMD, a number of exogenous variables were examined but this was consistently the best formulation considering model fit, predictive ability and model parsimony.

Coefficient estimates and summary statistics for these models are presented in Table 3. Figures 1 and 2 show the fitted response surface for each data set.

%Decay Model - The %decay model can be used to estimate the actual amount of decay which can be expected in a stand given certain stand conditions. The volume of decayed wood can be calculated as the %decay (obtained from equations [8] and [9]) times the estimate of merchantable volume in an inventory. A number of linear an d nonlinear models were examined, scrutinized, and compared with the two best given below:

$$\%decay = a \left(\frac{SI}{QMD} \right)^{b} \qquad [8]$$

$$\%decay = a \left(\frac{SI}{QMD} \right)^{b} e^{(c\ CROWN)} \qquad [9]$$

As with equations [1] and [2], it is suggested that the model having CROWN included be used whenever possible. CROWN, the average crown ratio, is an easily measured yet under-utilized variable and is an important addition to the model.

Coefficient estimates and summary statistics for these models are also provided in Table 3.

Although the coefficients for the ONTARIO and the LCMR data sets were quite different, the variables which proved to be most important in explaining either the risk or the quantity of decay were quite consistent. This certainly lends justification to the basic approach and model form.

Models [7]-[9] provide simple yet reliable estimates of both %decay and a risk index which land managers in Northern Minnesota and Ontario can use with existing inventory databases. It is suggested that the LCMR Data results be used for locations in Northern Minnesota. In addition, the models are simple enough that they can easily be implemented via a GIS.

Table 3. Coefficient estimates and summary statistics for final decay models.

Equation Number	Sample Size	a	b	c	R^2	|e|
	LCMR Data					
7	53	3.9435	-0.6399	N/A	N/A	N/A
8	53	205.5415	-1.4330	N/A	0.24	5.24
9	53	640.9472	-1.5749	-0.0583	0.38	4.38
	Ontario Data					
7	83	8.6014	-2.3220	N/A	N/A	N/A
8	83	398.1841	-2.4139	N/A	0.19	3.9435

Further details on the analysis and results can be found in:

Walters, D.K. 1993. Final Technical Report for the LCMR funded project, "Aspen Decay Models in Northern Minnesota" (in preparation).

B.6. Benefits: Forest management decisions, ranging from decisions about long-term planning to those concerning the choice of stands for immediate harvest depend on a knowledge of the health of the forest. Foresters are making decisions concerning which stands (or portions thereof) to harvest and which to leave every day. These stands have varying degrees of resistance to decay. The analysis as proposed here would summarize this information and present it in a useful and straight forward manner. The results will indicate which stands should be cut now and which can be retained for several years. Such decisions can have a marked effect on future timber supply by providing for wood fiber maximization within multiple use forest management concepts.

IV. Evaluation

For the FY92-93 biennium the program can be evaluated by its ability to: 1)assemble a quality data set for modeling aspen decay in mature stands; 2)express the relationships between aspen decay levels and stand level parameters quantitatively and 3)package the quantitative expression of the relationships in a format that is both straight-forward and useful to forest managers.In a broader sense, this program can be evaluated on its contribution to a clearer understanding of the aspen supply issue and the implications of an aging aspen resource. In addition, the methodology developed herein should be useful for evaluating decay in other species. The degree to which the methodology is extrapolated to other species is certainly a useful criteria for evaluation.

V. Context

A. Current and previous work in aspen decay addresses many questions but does not address the question of which stands can be kept from harvest and which stands should be harvested before decay loss becomes serious. With recent growth in computerized inventories, stand level information is routinely available to many field foresters. This study will develop relationships between aspen decay and this stand level information which can assist the forester in choosing stands for harvest.

B. This work will supplement previous work because many of the questions previously addressed can be answered better with this additional data. And, in addition, we propose to use previous work to supplement our data and our results.

C. There have been no past LCMR funds used in this area. Besides aspen, there are a number of species for which a better understanding of decay relationships needs to be found. These could certainly be proposed for LCMR funding at a future date with techniques evolved from this study.

D. Not applicable.

E. Biennial budget system program title and budget: Not available at this time.

VI. Qualifications

A. Program Manager:

Mr. Dennis Hummitzsch
Land Commissioner
Koochiching County, Minnesota

Mr. Hummitzsch has a B.S. in Forest Science from the University of Wisconsin - Madison. Currently, the program coordinator has responsibility to direct and administer the forest management of 284,000 acres of public land in Koochiching county, Minnesota. Management of this resource has a regional impact regarding not only wood fiber supply but also other amenity uses. His prior experience has been varied as a field forester during the past 15 years.

Mr. Hummitzsch's primary role will be as program coordinator and to make certain that the results of this research will be directly and easily applied in practice. In addition, he will help to screen, identify, and locate appropriate stands in which field data will be collected within Koochiching county.

B. Major Cooperators:

1. Mr. David K. Walters
Research Specialist
Department of Forest Resources, University of Minnesota

Mr. Walters joined the faculty at the University of Minnesota in 1988 and his duties include the technical and administrative leadership of the Great Lakes Forest Growth and Yield Cooperative. Concurrently, he is working on a doctorate degree in forestry. He has worked on a number of aspects of forest growth and yield at Oregon State University, Virginia Tech, Boise Cascade Corporation, and the University of Minnesota. He is the author of numerous technical publications on forest growth modelling and planning methodology.

Mr Walters primary role will be to organize and supervise field data collection (Objective A) and to provide the statistical and analytical expertise for completing Objective B.

List of Publications (partial)

Walters, D.K., A.R. Ek, and D. Czysz. 1990. Construction of variable density empirical yield tables from forest management inventory data. Northern Journal of Applied Forestry (IN PRESS).

Walters, D.K., and A.R. Ek. 1990. Development and application of a state-wide empirical growth and yield model for natural aspen stands. IN: Proceedings of Aspen Symposium '89, Duluth, MN, July 25-27, 1989. U.S.D.A. Forest Service General Technical Report NC-140. pp. 177-183.

Walters, D.K., T.G. Gregoire, and H.E. Burkhart. 1989. Consistent estimation of site index curves. Biometrics 45:23-33.

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Walters, D.K., D.W. Hann, and M.A. Clyde. 1985. Equations and tables predicting gross total stem volumes in cubic feet for six major conifers of Southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, OR. Research Bulletin 50. 37pp.

2. Dr. Chung-Muh Chen
Senior Research Analysis and Forest Biometrician
Division of Forestry, Minnesota Department of Natural Resources

Dr. Chen is the Senior Research Analyst with the DNR Division of Forestry. His major role in the Division is the analysis of forest resources for timber supply, growth and yield, and the design of sampling methods for forest inventory. Dr. Chen has published papers in Forest Science, the Journal of Forestry, University of Minnesota Research Notes, and as US Forest Service North Central Experiment Station Technical Notes.

Dr. Chen's primary role will be to provide assistance with obtaining existing data (described in Objective A) and with providing expertise to assist with the statistical modeling (Objective B).

3. Dr. Alan R. Ek
Professor and Department Head
Department of Forest Resources, University of Minnesota

Dr. Ek is Professor and Head, Department of Forest Resources, College of Forestry, University of Minnesota, St. Paul. He joined the faculty there in 1977, after serving on the forestry staff of the University of Wisconsin, Madison, since 1969. He is the author of more than 130 technical publications on forest sampling, forest growth modelling and planning methodology and a member of Xi Sigma Pi, Sigma Xi, Biometric Society, IUFRO, the American Society of Photogrammetry and Remote Sensing and the Society of American Foresters (SAF). He has served as the Measurements Subject Area Representative on the Forest Science and Technology Board of the SAF, on the editorial advisory board of ***Forest Science***, as a working group secretary (Biometrics) and as Minnesota SAF State Policy Chair. He is a frequent consultant on forest resource inventory design, forest growth modelling and research planning in the U.S. and worldwide.

Dr. Ek will provide consultation on design and measurement of the decay survey.

List of Publications (partial)

Ek, A. R. and R. A. Monserud. 1974. Trials with program FOREST: Growth and reproduction simulation for mixed species even- or uneven-aged forest stands. In: Growth models for tree and stand simulation. J. Fries (ed.). IUFRO Working Party 1S4.01-4. Proceedings of 1973 Meetings. Royal College of Forestry Research Notes No. 30. pp. 56-73. Stockholm.

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Isebrands, J. G., A. R. Ek and R. S. Meldahl. 1982. Comparison of growth model and harvest yields of short rotation intensively cultured Populus: a case study. Canadian Journal of Forest Research 12: 58-63.

Martin, G. L. and A. R. Ek. 1984. A comparison of competition measures and growth models for predicting plantation red pine diameter and height growth. Forest Science 30:

731-743.

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VII Reporting Requirements

Semiannual status reports will be submitted not later than January 1, 1992, July 1, 1992, January 1, 1993 and a final status report by June 30, 1993.

July 1, 1993

LCMR Final Status Report - Detailed for Peer Review - Research

I. Development of Aspen Decay Models for Mature Aspen Stands - Forestry 21

Program Manager: Dennis Hummitzsch, Land Commissioner
Koochiching County Land Department
International Falls, MN
(218)283-6295

A. M.L. 91 Ch.254, Art. 1 Sec.14 Subd: 7.g — Appropriation: $85,000; Balance: $0

Aspen Decay Models for Mature Aspen Stands: This appropriation is to the commissioner of natural resources to contract with Koochiching county and the University of Minnesota, College of Natural Resources, to develop models for aspen decay in mature aspen stands.

B. Compatible Data: Not applicable

C. Match Requirement: Not applicable

II. Narrative

The amount of aspen timber volume which is lost to decay is assumed to be large in Minnesota. Forest managers need more information on managing mature aspen stands so that this loss is minimized. By understanding the relationship between individual-stem decay and stand characteristics, decisions can be made as to which mature stands should be harvested first, which can be left, and how long stands can be left before the decay loss is critical. The accuracy of long-range planning efforts can be increased by incorporating this new information into existing growth and yield models. Given the increasing pressure on Minnesota's aspen resource, accurate long-term planning and forecasting is critical. This new information will also be developed in the form of indices which classify stands as to their vulnerability to decay (risk-level) based on stand characteristics such as soil type, site index, and age. These indices could be easily placed into existing geographic information systems to serve as an aid for site specific harvesting operations.

III. Objectives

A. Develop and implement a sample design (survey) to obtain data relating Aspen decay and stand characteristics.

A.1. Narrative: While relationships between inner-stem decay and outer-stem characteristics are well documented, the relationship to stand-level characteristics such as soil type, site index, and age is still vague. An effective survey will be developed in cooperation with the Minnesota DNR and other researchers in the field.

A.2. Procedures:

A key to the success of this project is obtaining data from a broad cross-section of stand conditions in Northern Minnesota and other similar locales. In addition to being prohibitively expensive, collecting all "new" data is unnecessary. Data for this project may come from two sources:

1. Previous studies of aspen decay having the necessary variables. These studies may or may not have looked at relationships between decay and stand characteristics but could be used for this purpose.

The Minnesota Department of Natural Resources recently conducted an aspen decay project (A. Jones and O. Phillips, Minnesota DNR Aspen Loss Assessment Work Plan, 1989). While this project did not specifically look at the question of how aspen decay relates to stand characteristics it does provide some of the data necessary to look at that question.

A study conducted by the Ontario Ministry of Natural Resources in northwestern Ontario also provides appropriate data (R. Miller, et. al., Ontario Ministry of Natural Resources 1990, Proposed Methodology Enhancements of Trembling Aspen Soil Site/Productivity Relationships in Northwestern Ontario). This study involved remeasuring a large number of permanent plots and felling a number of associated trees for stem analysis.

Initial conversations with these two projects indicate that we will most likely be able to use the data from these projects in this study and effectively increase our sample size. This in turn will result in a larger regional applicability to any relationships which we can model.

In addition to these two recent efforts, there are also a number of older studies which may prove useful:

Maier, G.B. and D. Darrah. 1972. Decay levels in mature aspen stands, Whitecourt, Alberta, Canada. Alberta Forest Resource Development Agreement Project no. 1467-72. 376 pp.

Schmitz, H. and L. W. R. Jackson. 1927. Heart rot of aspen with special reference to forest management in Minnesota. University of Minnesota Agricultural Experiment Station Technical Bulletin 50. 43 pp.

Morawski, Z. J. R., J. T. Basham, and K. B. Turner. 1958. Survey of pathological condition in the forests of Ontario. Ontario Department of Lands and Forests, Division of Timber, Report no. 25 (co-studies) 96 pp.

Gevorkiantz, S. R. and W. A. Duerr. 1938. Methods of predicting growth of forest stands in the forest survey of the Lake States. USDA Forest Service, Lake States Forest Experiment Station, Economic Notes no. 9. 59 pp.

As much useful data as possible will be assembled from reports and historical records.

2. Field data collected specifically for this project.

This data source will certainly be the bulk of the data for this project. A number of factors need to be considered in order to collect useful data. Plots will be established in either the aspen-birch unit or northern pine unit of the statewide (Phase I) inventory in order to overlap measurements of this inventory taken in 1988-1990 and at earlier inventories. The primary emphasis will be in Koochiching and St. Louis counties because of the large acreage in mature aspen stands found in this county.

Using the phase II forest management inventory state and county lands in the area, potential stands for data collection will be located that are 1)in the Aspen cover type, 2)within one mile of a road, 3)between the ages of 20 and 80, and 4)have a site index greater than 40.

Critical to the success of the study is sampling stands over a wide range of age, site index, and tree size. Therefore, the following matrix of site quality versus stand age will be sampled as completely as possible (it is expected that tree size will be broadly distributed by sampling from this matrix):

Stand Age	Site Index			
	40 - 60	60 - 70	70 - 80	80+
21 - 30	4+ plots	4+ plots	4+ plots	4+ plots
31 - 40	4+ plots	4+ plots	4+ plots	4+ plots
41 - 50	4+ plots	4+ plots	4+ plots	4+ plots
51 - 60	4+ plots	4+ plots	4+ plots	4+ plots
61 - 70	4+ plots	4+ plots	4+ plots	4+ plots
71+	4+ plots	4+ plots	4+ plots	4+ plots
Total	24+	24+	24+	24+

Our goal will be to have a minimum of four field plots in each cell. Where some cells can be completed with data from previous studies we may collect less field data. One plot will be considered one observation in the cell of the above mentioned matrix. To save on travel costs and be more effective in the field, these plots may be clustered within stands or within locales.

Each plot will consist of nested 1/15th (30.4 feet radius) acre and 1/100 acre fixed radius plots. All trees larger than 5" will be tallied on the 1/15th acre plot and trees greater than 1" but less than 5" will be tallied on the smaller plot. On each plot, all trees >1" diameter at breast height will be measured for species, diameter, total height, height to live crown base, and indicators of decay problems will be noted. In addition, degree of closure of the crown canopy, aspect, slope, observation of recent disturbance, site quality, and soil type will be recorded for each plot. Site index will also be calculated for each plot based on the height and age of three dominant/codominant trees located on or near the plot. Where appropriate, these site trees will also provide an estimate of stand age.

Alternatively, available records may provide a good estimate of age. Measurement and coding of stand variables will be consistent with the existing Phase I permanent plot system.

Following measurement of the plot, four trees will be selected randomly within the available diameter classes from each plot. These trees will be felled at 0.5-foot stump height and sectioned at breast height (4.5 feet) and at 4-foot intervals thereafter to the tip. After felling, total tree length and length of live crown will be measured. Each section will be inspected for the presence of conks, cankers, borer activity and decay. The location of each of these on each section will be recorded with an appropriate symbol on a map of each 4-foot section. Species of conks and causal agents of cankers will be identified using macroscopic characteristics. The width of conks at their widest point and the length of cankers will be recorded.

The cross-sectional face of each section will then be examined for the presence of decay. Three stages of decay will be distinguished; incipient, intermediate and final. Incipient decay will consist of wood that is faintly colored from a light pink to straw brown. The intermediate stage includes all degrees of coloration from straw to brown but wood is apparently still hard and firm. Final stage includes [illegible]t, punky wood (or missing wood) irrespective of color.

The area of each cross section which is solid or decayed will be determined by one of two methods. The first will involve placing a transparent grid over the stem cross-section. Boundaries of the stem and each stage of decay will be traced onto the grid. This grid will then be planimetered or digitized in the office to arrive at estimates of the amount of decay and sound wood in the cross-section. The second possible method will involve photographing each cross section in a standard fashion so that the photographs could then be planimetered or digitized as above (This technique has been used with success before - Goelz, J.C.G. and T.E. Burk. 1987. Testing a photographic method for measuring stem cross-sections. Forest Science 33(3):784-89). The choice of method will be made after additional review.

The areas in decay and sound wood will be converted to volumes via standard mensurational formulas (e.g., smallans volume formula for the majority of the bole, cylindrical and conic volume formulas at the base and tip, respectively)

Finally, each plot will be located on a map or existing aerial photography such that additional large-scale photography can be obtained at a later date. This photography may be used to identify clonal differences within a plot and to provide additional stand variables that might typically be available to forest managers. To evaluate the efficacy of using aerial photography to identify clonal differences, bud or leaf samples will be collected from each tree on the plot. These will be subjected to protein analysis which can help to identify genotype (personal communication, Dr. Glenn Furnier, Univ. of Minnesota, Department of Forest Resources).

A.3. Budget

	LCMR Funds	Matching Funds
a. Amount Budgeted:	$50,000	$0
b. Balance:	$0	$0

The contract between the DNR, the University of Minnesota, and Koochiching county defines specific objectives which result in specific disbursements of dollars.
All tasks were completed and notice of this forwarded to the DNR who then arranged for payment.

A.4. Timeline for Products/Tasks

Timeline for Products/Tasks	July91	Jan92	June92	Jan93	June93
Historical/existing data acquisition	-------------|				
Develop survey and field guidelines	--|				
Field data collection	|------|				
Aerial photo data collection	|-|				
Keypunching of field data		|-----|			
Aerial photo interpretation		|-----|			
Tissue analysis for clonal difference			|--|		

A.5. Status:

Data have been obtained from several historical studies. Data from 83 aspen stands in Ontario have been obtained from the Ontario Ministry of Natural Resources. These data were collected from 1/10 acre fixed radius plots upon which all trees were felled and sectioned. The volume of healthy and decayed wood was calculated by graphing each tree in 2 dimensions (width, height). Assuming the tree cross-sections were round, these graphs were used to calculate the merchantable pulpwood) volume and the net ((of decay) merchantable pulpwood volume. These data were collected in the mid 1950's and are henceforth referred to as the Ontario Data. As an aside, several hundred more plots are available from stands classified as other forest types. At some point, the models developed in this study will be extended to the other forest types for Ontario.

[illegible] were also obtained from a 1990 study conducted by the Minnesota [illegible]. However these data do not have the stand-level information necessary for this work.

The aspen data collected by the USFS FIA (Forest Inventory and Analysis) Project have also been obtained. FIA plots can be classified as full or partial measurements. Only the full measurement plots have any information on decay actually observed on the plot; this information being estimates of decay based on external stem indicators such as conks, cankers, and wounds. These full measurement FIA data are henceforth referred to as the FIA Data.

The data collected in the summers (July-Sept.) of 1991 and 1992 under this project consists of 53 plots located across Koochiching and St. Louis counties in Northern Minnesota. 500 trees were felled and sectioned, providing detailed information on individual tree volume and decay. In addition, other more traditional measurements were made on 11156 standing trees. These data have all been keypunched and checked for errors. These data are henceforth referred to as the LCMR Data. A formal survey design and set of field guidelines were developed and used in completing the field work.

All data have been incorporated into a relational database management system to (a) facilitate analysis and (b) serve as a central storage base. A listing of the database structure (tables and variables), as well as copies of the survey design and field guideline documents are available from David Walters (612/624-3400), University of Minnesota, Dept. of Forest Resources. In total, the database requires approximately 20 megabytes of physical disk space.

A.6. Benefits: In addition to providing information for objective B, objective A would provide valuable data for other, future efforts in characterizing forest growth, development, and yield. Some examples are individual stem volume and taper equations, and climate change impact analyses. This data would be maintained by the Great Lakes Forest Growth and Yield Cooperative located at the University of Minnesota and be made available to researchers upon request.

B. Develop relationships between aspen stem quality and forest stand characteristics

B.1. Narrative: Individual stem quality would be related to stand characteristics through various multivariate statistical analysis and modeling techniques.

B.2. Procedures:

Actual and Percent volume in sound wood, incipient, intermediate and final stages of decay will be developed for each tree that is felled and sectioned. Using appropriate expansion factors these values will be expanded to a per acre basis for each stand.

Multivariate analysis techniques will be used to relate exogenous variables such as average stand diameter, quadratic mean diameter of the stand, site index, average height, average crown ratio, percent crown closure, basal area, trees per acre, and other variables to the different endogenous variables including absolute and percent decay (each type) and various transformations.
Initially, extensive use of graphing techniques will be made to identify appropriate relationships between these variables. As an example, a three-dimensional graphical analysis of final stage decay, site index and age will enable us to see if there is any 2 or 3 dimensional relationship between the three variables.

Model estimation will rely on linear and nonlinear regression, and may include principle component analysis. Principal component analysis may help to identify linear combinations of the variables that provide a more parsimonious description of the relationships.

A guiding criteria will be that any developed equations will facilitate the estimation of decay levels from commonly available stand characteristics or combinations thereof. In essence this will lead to a better understanding of the economic rotation age of aspen or equivalently, how long aspen can be held on the stump while minimizing wood fiber loss.

Further analysis will involve relating our conclusions about aspen decay to the aspen decay relationships found in both phase I and phase II Minnesota statewide inventories as well as in surveys we will determine estimates of decay for a number of stands and then compare our estimates with those found in the survey. The results should provide more accurate decay estimates for these surveys.

Upon completion of the statistical analysis and modeling, the results will be incorporated into an existing growth and yield model and into the GIS system of Koochiching county. This will help facilitate the use of these results by integrating the information into a field usable format. GIS maps are used on a daily basis as well as for future planning. It will also serve as a model for other counties.

Results of the project will be presented at least once at an annual meeting of the Great Lakes Forest Growth and Yield Cooperative. The members of this Cooperative include local/state/federal/industry foresters and land managers. Within Minnesota, non-member local government officials (county land commissioners) will also be invited to the presentations. In addition, summary reports will be distributed to appropriate land commissioners within Minnesota.

B.3. Budget:

	LCMR Funds	Matching Funds
a. Amount Budgeted:	$35,000	$0
b. Balance:	$0	$0

The contract between the DNR, the University of Minnesota, and Koochiching county defines specific objectives which result in specific disbursements of dollars. All tasks were completed and notice of this forwarded to the DNR who arranged payment.

B.4. Timeline for Products/Tasks

```
Timeline for Products/Tasks        July91  Jan92   June92  Jan93   June93

- organize data                            |-|     |-------|
- graphical analysis                       |---|
- statistical analysis                     |-------------------------|
- computer programming of
  results into existing
  growth models                                            |---------|
_ integration of results
  into GIS                                                     |-------|
- presentation of results                          |---|               |---|
- distribution of summary report                                         |-|
```

B.5. Status:

All of the data to be used in this project, historical data and that collected specifically for this project, have been combined into a relational database. Early in 1993, a preliminary report describing initial statistical analyses was provided to the Minnesota DNR for approval. Such approval was received and more detailed analyses followed.

Prior to beginning statistical analysis, many preliminary steps were taken to convert the variables observed on individual trees, i.e., diameter outside bark at breast height (D), tree height, crown length, etc., into variables useful from the context of modelling decay volume per acre or the percent of stand volume in decayed wood. To do this, a large number of intermediate computer programs were written and utilized. For the Ontario Data, these programs basically aggregated tree variables to a stand basis. As an example, the volume was recorded in the data for each tree based on stem analysis. These per tree merchantable pulpwood volumes were summed for each plot and the result multiplied by 10 (these were 1/10 acre plots) to obtain per acre merchantable pulpwood volumes. Similar aggregation was done for the FIA Data.

The LCMR data was more complicated as it involved felling and sectioning a large number of trees. These trees formed the heart of the information on decay and in order to eventually obtain the needed stand variables a number of auxiliary relationships were developed:

True individual tree Volumes - The true volume for all felled trees in the LCMR Data was calculated by summing the volumes of all sampled sections. Depending upon their location in the bole, the volume of individual sections was calculated by different means. Smallans formulae,

$$V_{smallans} = \frac{l\,(a_u + a_l)}{2}$$

was used for all sampled sections above breast height (4.5 feet). Note that l is the length of the section, a_u is the area of the upper (generally smaller) end and a_l is the cross-sectional area of the lower (generally bigger) end. The volume of the sections between the top of the stump and breast height was approximated as the frustrum of a neiloid,

$$V_{neiloid\ frustrum} = \frac{l}{4}\left(\frac{a_l - a_u}{\left(\frac{a_l}{a_u}\right)^{\frac{1}{3}} - 1} + a_l\right)$$

where l, a_u, and a_l are as defined above.

The volume of the stump was calculated as a cylinder,

$$V_{cylinder} = l\,a_u$$

Finally, the volume from the top of the last sampled section (generally coinciding with a merchantable top diameter outside bark (D_t) of 3 inches) to the tree top was calculated as a cone,

$$V_{cone} = (l\,a_l)^{\frac{1}{2}}$$

In order to fit (described later) a model of individual tree merchantable volume, it was necessary to obtain the true volume to a variety of top diameters. For those top diameters which fell above the last section actually sampled, the volume from the top of the last section to the desired top diameter was calculated as the frustrum of a cone.

By summing the volume of individual sections and doing appropriate interpolations, the true volume from any lower point to any upper point on the bole could be obtained for all felled trees. A variety of merchantability limits were applied and true volume calculated for the volume from stump to top diameters outside bark of 2, 3, 4, and 5 inches. In addition the total stem volume was calculated.

Lower Stem Diameter Inside Bark Equations- Because of an oversight the first year, the diameter inside bark at breast height (d) was not always observed. Therefore the following functions were postulated and fitted to the data collected the second year of the study:

$$d = aD^b \qquad [1]$$

and

$$d = aD^b e^{c\,CROWN} \qquad [2]$$

where a,b, and c are coefficients to be estimated and CROWN is the ratio of live crown length to total stem length (commonly referred to as crown ratio). Equation [2] was used in this work but [1] was developed as other studies may not have information on crown length or ratio. In addition, while the diameter inside bark at stump height (d_s) was always observed, the stump height varied and an equation predicting diameter inside bark at a consistent stump height (1.0 feet in this study) was required. The equation was:

$$d_s = \left(\frac{d}{a\ d^b}\right) + (4.5 - h_s) \qquad [3]$$

where h_s = stump height. Equation [3] is derived assuming the shape of the geometric solid between stump and breast height is that of a neiloid. Equations [1]-[3] were with weighted nonlinear regression assuming that the variance was proportional to D^2. Coefficient estimates and fit statistics are provided in Table 1.

Individual Tree Volume and Height Equations - To obtain the volume of each tree which consisted of wood in intermediate and final stages of decay, the geometric volume formulae above (Smallans, neiloid, cylinder, cone) were used along with the observed cross-sectional area of decay at the top and bottom of each cut section. Then, as with the individual tree volumes, the volume in decayed wood was calculated for each felled tree by summing the volumes of appropriate sections and making proper interpolations. From this an average percent decay was developed as

$$\%d = \frac{decay\ volume}{total\ volume}$$

Because the sampled (felled) trees were sampled at random, the observed average percent decay can be directly extrapolated to be the observed average decay for the plot when expressed on a percent basis.

It was also necessary to determine the volume on the remaining (non-felled) trees on each plot. Therefore equations were developed to estimate total height, total volume, and merchantable volume. Such equations are available elsewhere but given the quality of these data, it was best to develop new ones. Because it is appropriate to estimate volume below breast height from basic mensurational formulae (i.e., a neiloid frustrum), the volume equations fitted here were for the volume from breast height to some top diameter (0 inches in the case of total volume above breast height). The total tree volume, including the volume below breast height can then be easily obtained by addition.

$$V_t = V_{bbh} + V_{abh,d_t}$$

Note that when $d_t=0$, V_t is equal to total tree volume. As with equations [1]-[3], above, a number of possible equations were examined with the following being the best when compared as to fit and predictive ability.

$$h_{abh} = b_1\left(1 - e^{-b_2 D}\right)^{b_3} SI^{b_4} \qquad [4]$$

$$V_{abh,0} = a\left(\frac{h_{abh}}{D}\right)^{b} D^2\, h_{abh} \qquad [5]$$

$$V_{abh,d_t} = V_{abh,0}\left(1 - a\left(\frac{d_t}{D}\right)^{b}\right) \qquad [6]$$

where h_{abh} is the height from breast height to the top of the tree and SI is site index. All other variables have been previously defined. The coefficients and fit statistics for equations [4]-[6] are also shown in Table 1. Using the above functions, the merchantable volume on each tree on each plot was estimated as the volume from a stump height of 1.0 foot to a d_t of 3.0 inches..

Table 1. Coefficient estimates and summary statistics for equations [1]-[6].

Equation Number	Sample Size	a	b	c	d	R^2	|e|
1	237	0.9427	0.9832	N/A	N/A	0.99	0.16
2	237	0.9342	0.9805	0.04907	N/A	0.99	0.04
3	237	0.000174	2.4925	N/A	N/A	0.95	0.48
4	157	12.4514	0.2273	1.6186	0.4273	0.82	3.49
5	483	0.001855	0.1083	N/A	N/A	0.95	1.32
6	1752	0.7636	3.9749	N/A	N/A	0.93	0.14

Other stand-level variables such as basal area per acre (BA, ft^2/acre), number of trees per acre (TPA), and quadratic mean diameter (QMD) were calculated as appropriate,

$$BA = EXPAND \sum_{i=1}^{n} .005454154 D^2$$

$$TPA = EXPAND\; n$$

$$QMD = \left(\frac{BA}{TPA}\right)^{\frac{1}{2}}$$

where n is the number of trees on the plot and EXPAND is the reciprocal of plot size (in the case of the LCMR data, EXPAND = 1/ (1/7) or 7.0). Only trees greater than or equal to 5.0 inches at breast height were included in these calculations. This restriction was due to the fact that the end goal of this project was that the models be readily applicable to many data sets. The data collected by most land management agencies in the Lake States generally coincides with this threshold value.

Similar aggregation was done for the Ontario and FIA Data as well.

Following these preliminary steps, three data sets as described in Table 2 were available. A large number of additional variables, including observations of simple soil traits, average phenology (bark coloration, leaf size, etc.) were also available but preliminary analysis suggested that those variables in Table 2 were the most promising. .

Table 2. Description of LCMR, Ontario, and FIA data sets.

Variable	Data Set								
	LCMR			Ontario			FIA		
	min	mean (s.d.)	max	min	mean (s.d.)	max	min	mean (s.d.)	max
Decay (%)	0.9	10.5 (7.7)	34.0	0.8	15.7 (11.1)	54.0	0.0	7.2 (7.5)	41.3
Stand Age (years)	0.8	45.8 (12.3)	68.0	44.0	94.1 (30.5)	157.0	2.0	45.5 (21.0)	103.0
Site Index (ft)	54.4	72.3 (8.7)	94.8	24.7	37.8 (5.7)	50.1	24.0	66.8 (11.1)	91.0
Basal Area (ft^2/acre)	2.5	109.7 (46.2)	210.5	47.4	152.4 (44.0)	312.1	3.8	66.8 (36.8)	183.8
No. of Trees per Acre	15.0	262.6 (95.8)	480.0	130.0	304.5 (105.)	590.0	7.6	159.2 (90.8)	393.3
Quadratic Mean Diameter (Inches)	5.5	8.8 (2.0)	13.9	5.8	9.9 (2.0)	14.0	5.5	9.0 (1.8)	16.5
Average Crown Ratio	5.2	15.6 (5.3)	30.0	N/A	N/A	N/A	N/A	N/A	N/A

Initial analyses revealed that the FIA data did not contain any useful (in the context of modelling) relationships between %decay and any stand-level attributes. No statistically significant relationships could be found. This was to some extent anticipated due to the inherent nature of the FIA plot design. These plots are actually clusters of 10 small variable radius plots. This confounds the classification of the plot as to forest type, the determination of age and site index, and many otherwise useful stand level variables. Therefore the %decay models were developed with the LCMR and Ontario Data only.

Once the data described in Table 2 were assembled, the modelling of decay on a whole stand or per acre basis was begun. Two basic model formulations were desired,

Risk Index Model - The risk index model was formulated in the context of logistic regression and is meant to be used to rank stands as to their probable risk level to significant incidence of decay. A binary variable was developed having a value of 1 when the amount of decay exceeded 15% and a value of 0 when the amount of decay was less than 15%. Logistic regression was then used to fit the function:

$$Y_{0,1} = \frac{e^{a + b\left(\frac{SI}{QMD}\right)}}{1 + e^{a + b\left(\frac{SI}{QMD}\right)}} \qquad [7]$$

This model was fitted by minimizing the following loss function which provides maximum likelihood estimates of a and b:

$$\sum_{i=1}^{n} Y_{0,1} \log(\hat{Y}_{0,1}) + (1 - Y_{0,1}) \log(1 - \hat{Y}_{0,1})$$

In addition to SI/QMD, a number of exogenous variables were examined but this was consistently the best formulation considering model fit, predictive ability and model parsimony.

Coefficient estimates and summary statistics for these models are presented in Table 3. Figures 1 and 2 show the fitted response surface for each data set.

%Decay Model - The %decay model can be used to estimate the actual amount of decay which can be expected in a stand given certain stand conditions. The volume of decayed wood can be calculated as the %decay (obtained from equations [8] and [9]) times the estimate of merchantable volume in an inventory. A number of linear an d nonlinear models were examined, scrutinized, and compared with the two best given below:

$$\%decay = a\left(\frac{SI}{QMD}\right)^{b} \qquad [8]$$

$$\%decay = a\left(\frac{SI}{QMD}\right)^{b} e^{(c\ CROWN)} \qquad [9]$$

As with equations [1] and [2], it is suggested that the model having CROWN included be used whenever possible. CROWN, the average crown ratio, is an easily measured yet under-utilized variable and is an important addition to the model.

Coefficient estimates and summary statistics for these models are also provided in Table 3. Figures [3]-[9] show the actual and estimated %deca us a number of independent variables.

Although the coefficients for the ONTARIO and the LCMR data sets were quite different, the variables which proved to be most important in explaining either the risk or the quantity of decay were quite consistent. This certainly lends justification to the basic approach and model form.

Models [7]-[9] provide simple yet reliable estimates of both %decay and a risk index which land managers in Northern Minnesota and Ontario can use with existing inventory databases. It is suggested that the LCMR Data results be used for locations in Northern Minnesota. In addition, the models are simple enough that they can easily be implemented via a GIS.

Table 3. Coefficient estimates and summary statistics for final decay models.

Equation Number	Sample Size	a	b	c	R^2	lel
	LCMR Data					
7	53	3.9435	-0.6399	N/A	N/A	N/A
8	53	205.5415	-1.4330	N/A	0.24	5.24
9	53	640.9472	-1.5749	-0.0583	0.36	4.36
	Ontario Data					
7	83	8.6014	-2.3220	N/A	N/A	N/A
8	83	396.1841	-2.4139	N/A	0.19	3.9435

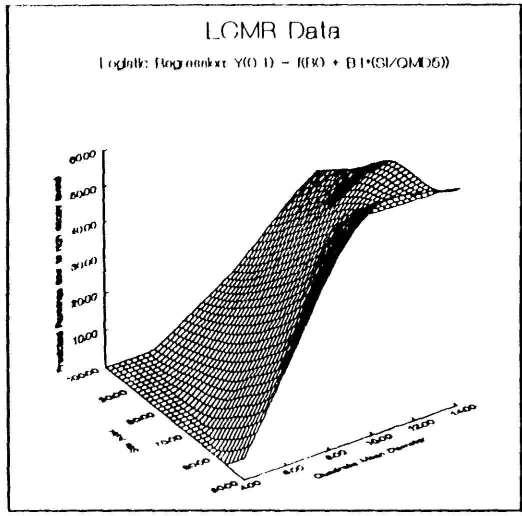


Figure 1. Response surface of risk index model for LCMR Data versus site index and quadratic mean diameter.

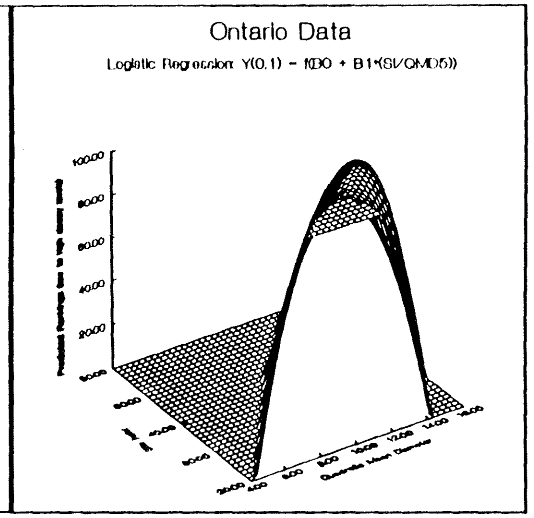


Figure 2. Response surface for risk index model for Ontario Data versus site index and quadratic mean diameter.

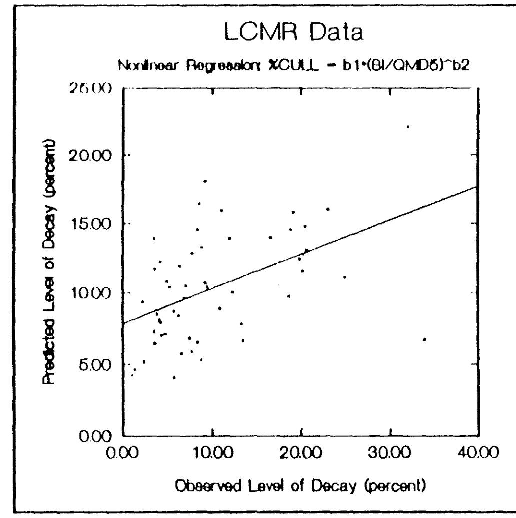


Figure 3. Predicted versus actual %decay using equation [8] and LCMR data.

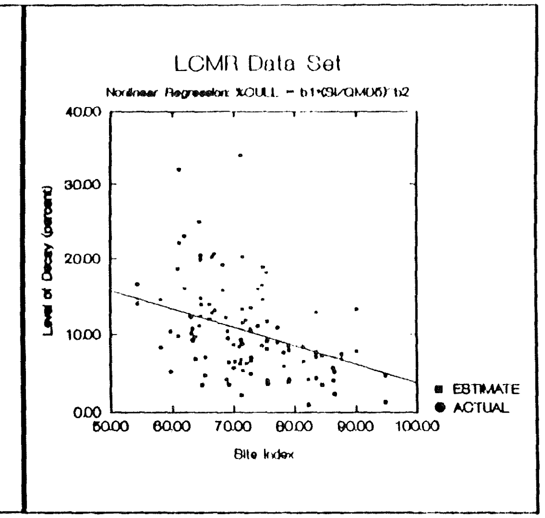


Figure 4. Predicted and observed %decay versus site index using equation [8] and LCMR data.

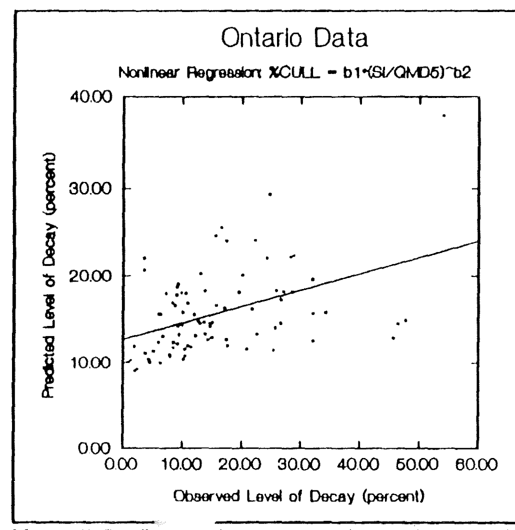


Figure 5. Predic[illegible]decay versus observed %decay for Ontario data and equation [8].

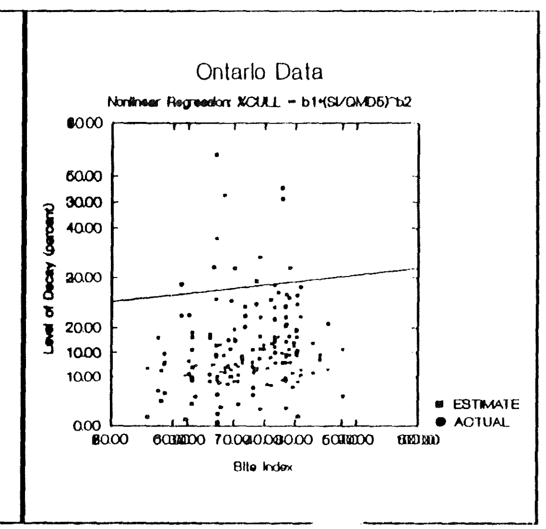
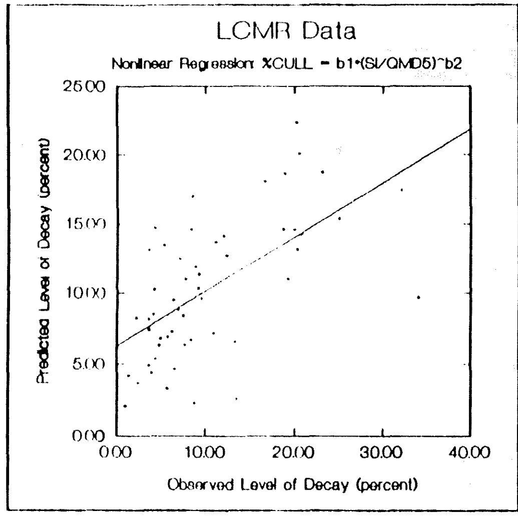


Figure 6. Predicted and obser[illegible]decay versus site index using equation [8] and Ontario data.



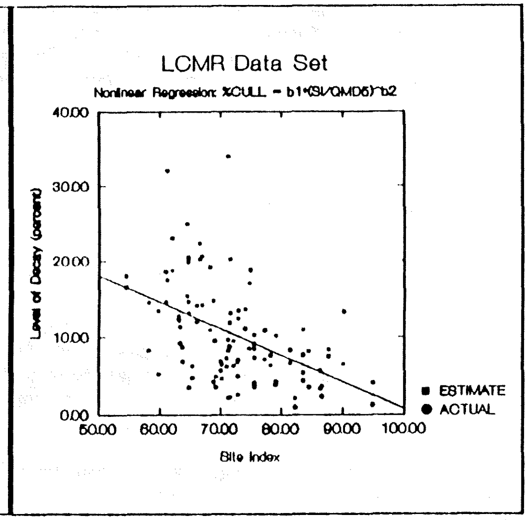
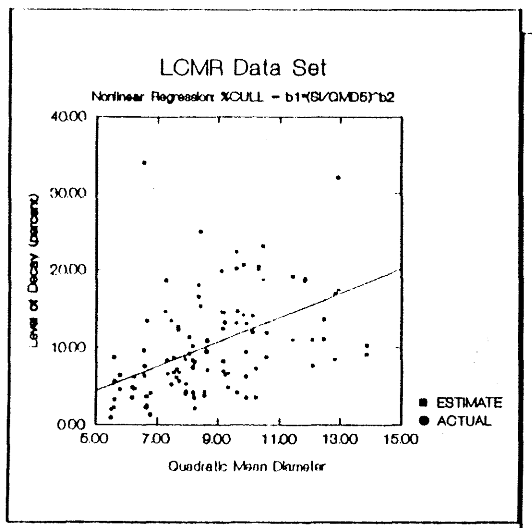


Figure 7. Predicted %decay versus observed %decay using [9] and LCMR data.

Figure 8. Predicted and observed %decay versus site index using equation [9] and LCMR data.



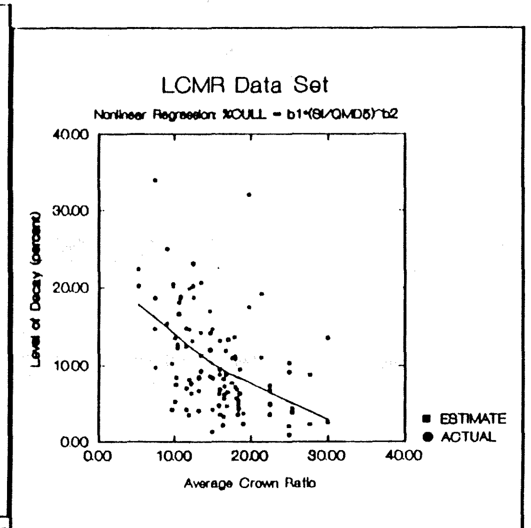


Figure 9. Predicted and observed %decay versus [illegible] [9] and LCMR

Figure 10. Predicted and observed %decay versus

Further details on the analysis and results can be found in:

Walters, D.K. 1993. Final Technical Report for the LCMR funded project, "Aspen Decay Models in Northern Minnesota" (in preparation).

B.6. Benefits: Forest management decisions, ranging from decisions about long-term planning to those concerning the choice of stands for immediate harvest depend on a knowledge of the health of the forest. Foresters are making decisions concerning which stands (or portions thereof) to harvest and which to leave every day. These stands have varying degrees of resistance to decay. The analysis as proposed here would summarize this information and present it in a useful and straight forward manner. The results will indicate which stands should be cut now and which can be retained for several years. Such decisions can have a marked effect on future timber supply by providing for wood fiber maximization within multiple use forest management concepts.

IV. Evaluation

For the FY92-93 biennium the program can be evaluated by its ability to: 1)assemble a quality data set for modeling aspen decay in mature stands; 2)express the relationships between aspen decay levels and stand level parameters quantitatively and 3)package the quantitative expression of the relationships in a format that is both straight-forward and useful to forest managers.In a broader sense, this program can be evaluated on its contribution to a clearer understanding of the aspen supply issue and the implications of an aging aspen resource. In addition, the methodology developed herein should be useful for evaluating decay in other species. The degree to which the methodology is extrapolated to other species is certainly a useful criteria for evaluation.

V. Context

A. Current and previous work in aspen decay addresses many questions but does not address the question of which stands can be kept from harvest and which stands should be harvested before decay loss becomes serious. With recent growth in computerized inventories, stand level information is routinely available to many field foresters. This study will develop relationships between aspen decay and this stand level information which can assist the forester in choosing stands for harvest.

B. This work will supplement previous work because many of the questions previously addressed can be answered better with this additional data. And, in addition, we propose to use previous work to supplement our data and our results.

C. There have been no past LCMR funds used in this area. Besides aspen, there are a number of species for which a better understanding of decay relationships needs to be found. These could certainly be proposed for LCMR funding at a future date with techniques evolved from this study.

D. Not applicable.

E. Biennial budget system program title and budget: Not available at this time.

VI. Qualifications

A. Program Manager:

Mr. Dennis Hummitzsch
Land Commissioner
Koochiching County, Minnesota

Currently, the program coordinator has responsibility to direct and administer the forest management of 284,000 acres of public land in Koochiching county, Minnesota. Management of this resource has a regional impact regarding not only wood fiber supply but also other amenity uses. His prior experience has been varied as a field forester during the past 15 years.

Mr. Hummitzsch's primary role will be as program coordinator and to make certain that the results of this research will be directly and easily applied in practice. In addition, he will help to screen, identify, and locate appropriate stands in which field data will be collected within Koochiching county.

B. Major Cooperators:

1. Mr. David K. Walters
Research Specialist
Department of Forest Resources, University of Minnesota

Mr. Walters joined the faculty at the University of Minnesota in 1988 and his duties include the technical and administrative leadership of the Great Lakes Forest Growth and Yield Cooperative. Concurrently, he is working on a doctorate degree in forestry. He has worked on a number of aspects of forest growth and yield at Oregon State University, Virginia Tech, Boise Cascade Corporation, and the University of Minnesota. He is the author of numerous technical publications on forest growth modelling and planning methodology.

Mr. Walters primary role will be to organize and supervise field data collection (Objective A) and to provide the statistical and analytical expertise for completing Objective B.

List of Publications (partial)

Walters, D.K., A.R. Ek, and D. Czysz. 1990. Construction of variable density empirical yield tables from forest management inventory data. Northern Journal of Applied Forestry (IN PRESS).

Walters, D.K., and A.R. Ek. 1990. Development and application of a state-wide empirical growth and yield model for natural aspen stands. IN: Proceedings of Aspen Symposium '89, Duluth, MN, July 25-27, 1989. U.S.D.A. Forest Service General Technical Report NC-140. pp. 177-183.

Walters, D.K., T.G. Gregoire, and H.E. Burkhart. 1989. Consistent estimation of site index curves. Biometrics 45:23-33.

Gregoire, T.G. and D.K. Walters. 1988. Composite vector estimators derived by weighting inversely proportional to variance. Canadian Journal of Forest Research 18:282-284.

Walters, D.K., and Harold E. Burkhart. 1987. A method for localizing site index equations. IN: Proceedings of the IUFRO Forest Growth Modeling and Prediction Conference, Minneapolis, MN, August 24-28, 1987. University of Minnesota.
Hann, D.W., D.K. Walters, and J.A. Scrivani. 1987. Incorporating crown ratio into prediction equations for Douglas-fir stem volume. Canadian Journal of Forest Research 17:17-22.

Walters, D.K. and D.W. Hann. 1986. Predicting merchantable volume in cubic feet to a variable top and in scribner board feet to a 6-inch top for six major conifers of Southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, OR. Research Bulletin 52. 107pp.

Walters, D.K. and D.W. Hann. 1986. Taper equations for six conifer species in Southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, OR. Research Bulletin 56. 41pp.

Walters, D.K., D.W. Hann, and M.A. Clyde. 1985. Equations and tables predicting gross total stem volumes in cubic feet for six major conifers of Southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, OR. Research Bulletin 50. 37pp.

2. Dr. Chung-Muh Chen
Senior Research Analysis and Forest Biometrician
Division of Forestry, Minnesota Department of Natural Resources

Dr. Chen is the Senior Research Analyst with the DNR Division of Forestry. His major role in the Division is the analysis of forest resources for timber supply, growth and yield, and the design of sampling methods for forest inventory. Dr. Chen has published papers in Forest Science, the Journal of Forestry, University of Minnesota Research Notes, and as US Forest Service North Central Experiment Station Technical Notes.

Dr. Chen's primary role will be to provide assistance with obtaining existing data (described in Objective A) and with providing expertise to assist with the statistical modeling (Objective B).

3. Dr. Alan R. Ek
Professor and Department Head
Department of Forest Resources, University of Minnesota

Dr. Ek is Professor and Head, Department of Forest Resources, College of Forestry, University of Minnesota, St. Paul. He joined the faculty there in 1977, after serving on the forestry staff of the University of Wisconsin, Madison, since 1969. He is the author of more than 130 technical publications on forest sampling, forest growth modelling and planning methodology and a member of Xi Sigma Pi, Sigma Xi, Biometric Society, IUFRO, the American Society of Photogrammetry and Remote Sensing and the Society of American Foresters (SAF). He has served as the Measurements Subject Area Representative on the Forest Science and Technology Board of the SAF, on the editorial advisory board of ***Forest Science***, as a working group secretary (Biometrics) and as Minnesota SAF State Policy Chair. He is a frequent consultant on forest resource inventory design, forest growth modelling and research planning in the U.S. and worldwide.

Dr. Ek will provide consultation on design and measurement of the decay survey.

List of Publications (partial)

Ek, A. R. and R. A. Monserud. 1974. Trials with program FOREST: Growth and reproduction simulation for mixed species even- or uneven-aged forest stands. In: Growth models for tree and stand simulation. J. Fries (ed.). IUFRO Working Party 1S4.01-4. Proceedings of 1973 Meetings. Royal College of Forestry Research Notes No. 30. pp. 56-73. Stockholm.

Ek, A. R. 1974. Nonlinear models for stand table projection in northern hardwood stands. Canadian Journal of Forest Research 4: 23-27.

Ek, A. R. and R. A. Monserud. 1979. Performance and comparison of stand growth models based on individual tree and diameter class growth. Canadian Journal of Forest Research 9: 231-244.

Ek, A. R. and R. A. Monserud. 1981. Methodology for modell[illegible] [illegible]rest stand dynamics. In: Dynamic Properties of Forest Ecosystems. D. [illegible] [illegible]chle (ed.).

Cambridge University Press. 600 p. (pp. 37-52).

Isebrands, J. G., A. R. Ek and R. S. Meldahl. 1982. Comparison of growth model and harvest yields of short rotation intensively cultured Populus: a case study. Canadian Journal of Forest Research 12: 58-63.

Martin, G. L. and A. R. Ek. 1984. A comparison of competition measures and growth models for predicting plantation red pine diameter and height growth. Forest Science 30: 731-743.

Eriksson, M., A. R. Ek, and T. E. Burk. 1988. A framework for integrating forest growth and dendrochronological methods. Proceedings of IUFRO Forest Simulation Systems Conference, Berkeley, CA. Nov. 2-5, 1988 (in press).

VII. Reporting Requirements

Semiannual status reports will be submitted not later than January 1, 1992, July 1, 1992, January 1, 1993 and a final status report by June 30, 1993.