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LONG-TERM EVALUATIONS OF NORTHERN PIKE EXPERIMENTAL REGULATIONS IN MINNESOTA LAKES[1]

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Abstract.– The effects of maximum, minimum, and slot length limits (along with one catch-and-release regulation) on sizes and relative abundance of northern pike *Esox lucius* were evaluated in 23 Minnesota lakes. The regulations began in 1989-1998 and lasted 9-15 years. Pre-regulation information was available back to the 1970s so that evaluation periods covered 21-37 years in each lake. For experimental control, comparisons were made during the same extended period with reference populations from 47 ecologically similar lakes. Although regulations did not work in every lake, the broader-scale statewide finding was that regulations improved size structure of northern pike populations but produced no consistent trends in relative abundance. The improvements were detected against the backdrop of reference populations that initially appeared to have similar sizes and relative abundances of northern pike. Maximum length limits protecting fish over 20, 22, or 24 inches total length produced significant long-term increases in percentages of northern pike ≥ 24 inches and ≥ 30 inches compared with reference populations. The percentages of fish ≥ 20 inches increased in all three lakes with 30-inch minimum length limits, but improvements did not carry over to fish ≥ 30 inches. A mix of slot length limits produced results more difficult to interpret, but generally improved size structure. A meta-analysis incorporating all the length regulations indicated that changes in northern pike size structure in regulated lakes relative to unregulated lakes were very large for ecological experiments. However, these changes in size structure did not seem to affect yellow perch *Perca flavescens* and walleye *Sander vitreus* populations. Length limits protected large northern pike with the expectation that reduced yields were an acceptable trade-off for producing larger fish for recreational fisheries. This study revealed the range and magnitude of responses we can reasonably expect from length limits, as well as the substantial value of conserving large fish when the goal is improved population size structure.

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Recreational fishing in Minnesota has historically influenced northern pike *Esox lucius* populations. Recreational fishing is highly selective for large northern pike with creel surveys illustrating that fish over 24 inches compose a large portion of the harvest even though fish as small as 12-14 inches can be readily caught (Cook and Younk 1998). A result of this size selectivity, combined with historical increases in fishing effort, is that size structures of northern pike populations have suffered and fewer trophy-size northern pike are caught today. A unique analysis of long-term records from a fishing contest in northwestern Minnesota (Olson and Cunningham 1989) offered insights into the historical changes in northern pike size structure in response to increasing levels of exploitation by recreational fishing. Contest entries of northern pike 9.5 lb and larger peaked in 1948 and then steadily declined, with average weights of entered fish declining from 10.1 lb in the 1930s to 6.8 lb in the 1980s. Statewide angling regulations after 1947 included a daily bag limit of three northern pike, but no length limits. During the 1980s, increasing numbers of anglers and fisheries managers became concerned about the long-term declines in northern pike sizes, and advocated for more restrictive length-based regulations to improve opportunities for catching larger fish in at least some Minnesota waters. The daily bag limit was further modified in 1994 to allow only one northern pike over 30 inches in the daily bag limit of three fish, but there have been no other statewide restrictions on lengths of fish that could be harvested.

Long-term evaluations of length limit regulations for recreational fisheries are needed to effectively manage fish species with life spans of 10 or more years, yet long-term studies are not common in the literature. Reasons for the lack of long-term studies include poor funding of long-term monitoring programs, and monitoring protocols that have not been consistent over time (Margenau et al. 2008). In many cases, evaluations of length limit regulations have been case studies with no replication among water bodies, and have seldom included comparisons with reference fish populations for experimental control. In two of the earliest studies of northern pike length limits, minimum length limits of 18 inches (Snow and Beard 1972) and 22 inches (Kempinger and Carline 1978) were not found to be effective. The two case studies monitored northern pike populations for 4 years and 9 years, respectively, with results indicating that the minimum length limits were not restrictive enough to protect large northern pike. Snow and Beard (1972) and Kempinger and Carline (1978) contended that the length limits reduced yields, and that high natural mortality of protected-size fish more than compensated for decreased fishing mortality. Pierce et al. (1995) argued that length limits protecting northern pike under 22 inches would be counterproductive in lakes with good recruitment and slow growth of small northern pike. Evaluations of higher minimum length limits (26, 32, and 40 inches) in Wisconsin (Margenau et al. 2008) found inconsistent responses that were difficult to interpret, in part because evaluations had low sample sizes, consisted of only one year pre-regulation and one year post-regulation sampling, and the three control lakes showed high variability.

The Minnesota Department of Natural Resources (MNDNR) began experimenting with length-based regulations for northern pike in the late 1980s. The length regulations included maximum, minimum, and slot length limits. A study of slot length limits was initiated during 1989-1991 in five moderate size (313-627 surface acres) north-central Minnesota lakes (Pierce and Tomcko 1997). The five populations received slot length limits protecting fish 20-30 or 22-30 inches total length. During 1996-1997, a larger experimental initiative (Goeman and Radomski 1997) resulted in maximum length limits protecting fish larger than 20, 22, or 24 inches in 11 lakes. The maximum length limits were used in moderate to larger size (184-5,406 acres) central Minnesota lakes. A contrasting approach using minimum length limits was attempted in southern Minnesota. Three small (91-193 acres) southern Minnesota lakes were given 30-inch minimum length limits in 1998. A few other ad hoc regulations have also been evaluated. The ad hoc regulations included slot length limits in two very large (> 100,000 acres) lakes noted more for their walleye *Sander vitreus* populations, a slot length limit in a 10,945-acre northeast Minnesota lake, and a catch-and-release-only regulation in a 158-acre lake located in an urban setting.

The variety of these regulations reflects the considerable variety of northern pike population characteristics found within Minnesota's geographical setting, which grades from prairie in the southwest, to a more mixed central area including hardwood forests, and then to heavily forested glacial shield in the northeast. Lakes along this southwest to northeast axis tend to grade from shallow, turbid, and eutrophic waters in the southwest to deeper, more clear and oligotrophic waters in the northeast, with fish communities changing accordingly along this geographical axis (Moyle 1956). Minnesota's thousands of lakes have been further categorized into 44 ecological lake classes based on variables associated with lake basin size, shape, and depth, variables associated with chemical fertility of the lakes, and length of the growing season (Schupp 1992). Within this wide range of ecological settings, it is difficult to generalize about northern pike population characteristics. However, populations from lakes in southern Minnesota tend to be more limited in natural recruitment due to loss of habitat from agricultural and other shore-land development. In contrast, many populations in central and northern regions of the state have good natural recruitment that has historically supported a large recreational fishery. Levels of natural recruitment were the principal rationale for choosing which regulation to use. Maximum and slot length limits were used in lakes expected to have good or consistent natural recruitment, whereas minimum length limits were used where recruitment was more likely to be limited.

As a top-level predator, northern pike have the potential to both compete with and prey upon walleye, another important sport fish in Minnesota and elsewhere (Wesloh and Olson 1962; Colby et al. 1987). Yellow perch *Perca flavescens* is often a key component of the diet for both northern pike and walleye even when minnows and small centrarchids are readily available (Seaburg and Moyle 1964). Some researchers have even considered the northern pike-yellow perch predator-prey relationship to be an important controlling aspect of aquatic community structure in small lakes (Anderson and Schupp 1986; Goeman et al. 1990; Findlay et al. 1994; Craig 2008).

The usual goal of experimental regulations was to improve northern pike size structure and the purpose of this study was to quantify the long-term effects of experimental regulations on sizes and relative abundances of northern pike. Each of the experimental regulations listed above was in effect for periods ranging from 9 to 15 years. Pre-regulation information was available back to the early 1980s for all of the lakes, and in some cases back to the 1970s, so that a unique aspect of this study was the duration of the evaluation periods (21-37 years). Additionally, I evaluated how changes in the northern pike populations affected sizes of yellow perch, and relative abundances of both walleye and yellow perch in some of the regulation lakes. For experimental control, northern pike, walleye, and yellow perch population changes in regulation lakes were further compared with changes in populations from ecologically similar reference lakes in the same geographic areas and over the same extended time periods.

Study Lakes and Regulations

Maximum length limits were implemented in 11 lakes selected by fisheries managers in central and west-central Minnesota. The lakes fell into three ecological classifications (lake classes 22, 27, 31; Table 1) that are typified by moderate to large surface areas (one lake was 184 acres but the rest were 496-5,406 acres), relatively clear water, and hard to very hard (> 150 mg $CaCO_3$ /l) water; and the lakes historically had good natural recruitment of northern pike. Two lakes received length limits protecting northern pike 20 inches and larger; one lake received a 22-inch maximum length limit; and the other eight lakes received 24-inch maximum length limits. The regulations were enacted in May 1996 or May 1997 and were in effect through 2006 or 2007. Green Lake was an exception, with the regulation dropped after 2005. Changes observed in

Table 1. Ecological lake class, lake dimensions, and Secchi depth measurements for lakes with maximum and minimum length regulations for northern pike (shaded), and comparable information for reference lakes. Reference lakes had 3 fish/day bag limits, and after 1994, bag limits were further restricted to allow only one of the three fish to be over 30 inches long.

Lake	Ecological classification	Surface area (acres)	Percent littoral area	Maximum depth (ft)	Secchi depth (ft)	Regulation Length	Regulation Start date
			Maximum Length Limits				
Andrew	27	946	35	83	11.5	24-inch	1997
Big Birch	22	2,108	30	81	10.5	24-inch	1996
Big Swan	27	918	44	45	6.6	24-inch	1997
Burgen	31	184	29	43	6.3	24-inch	1997
East Battle	22	1,949	42	87	8.2	22-inch	1997
Green	22	5,406	38	110	8.0	24-inch	1997
Melissa	27	1,831	51	37	10.5	24-inch	1996
Rachel	27	496	25	65	7.9	24-inch	1997
Sallie	27	1,246	46	50	8.0	24-inch	1996
Sturgeon	27	1,405	35	40	9.9	20-inch	1997
Ten Mile	22	4,669	28	208	18.0	20-inch	1997
Big Floyd	27	1,178	73	34	8.0	Reference	
Big Pine	27	4,730	50	76	5.7	Reference	
Black Hoof	31	183	44	29	14.5	Reference	
Brophy	31	293	51	44	8.0	Reference	
Cotton	27	1,783	44	28	10.0	Reference	
Detroit	22	3,083	61	89	7.3	Reference	
Le Homme Dieu	22	1,744	44	85	8.0	Reference	
Marion	27	1,624	42	62	11.5	Reference	
Minnewaska	27	8,050	27	32	9.5	Reference	
North Lida	27	5,513	43	58	6.0	Reference	
Osakis	22	6,389	53	73	3.5	Reference	
Pine Mountain	22	1,567	47	80	6.1	Reference	
Rush	27	5,338	62	68	6.5	Reference	
Star	22	4,454	63	94	5.2	Reference	
Steamboat	22	1,756	30	93	7.5	Reference	
Toad	27	1,716	33	29	3.5	Reference	
Washburn	22	1,554	48	111	12.5	Reference	
			Minimum Length Limits				
Kelly-Dudley	30	125	62	60	8.0	30-inch	1998
Reeds	24	193	57	58	5.5	30-inch	1998
St. Olaf	29	91	56	33	4.0	30-inch	1998
Roemhildts	30	70	63	60	7.0	Reference	
Auburn	24	261	61	66	9.5	Reference	
Bavaria	24	162	40	66	5.0	Reference	
Fish	24	171	43	28	6.5	Reference	
Long	24	261	50	33	9.5	Reference	
Medicine	24	886	45	49	5.8	Reference	
Minnewashta	24	738	50	70	7.1	Reference	
Riley	24	297	37	49	3.5	Reference	
Sarah	24	574	65	59	2.7	Reference	

fish populations from maximum length limit regulation lakes were compared with changes observed in 17 reference lakes from the same geographic fisheries management areas. Reference lakes were other available waters of the same three ecological lake classes that had comparable sampling histories and were 183-8,050 acres surface area (Table 1).

Minimum length limits were imposed in three southern Minnesota lakes that had low to moderate levels of natural recruitment for northern pike. One lake, St. Olaf Lake, was historically stocked with hatchery fish to supplement recruitment. Ecologically, the lakes were small (91-193 acres), hard-water lakes with moderately good water clarity considering their location in southern Minnesota (Table 1). Beginning in May 1998, 30-inch minimum length limits were in effect at all three lakes through 2007. Comparable reference lakes in the same fisheries management area were not available except for Roemhildts Lake (Table 1), a 70-acre lake. Therefore, additional data were obtained from eight reference lakes (162-886 acres) that had comparable sampling histories and were in an adjacent management area in the Minneapolis metropolitan area north of the study lakes (Table 1).

Slot length limits were used in five moderate-size north-central Minnesota lakes with relatively clear water that traditionally had good natural recruitment of northern pike (Table 2). The lakes had similar surface areas (313-627 acres), but spanned four ecological lake classes because their basin shapes differed (littoral habitat ranged from 28% to 80% among the lakes). Two lakes received slot length limits protecting 22-30-inch northern pike in 1989; the other lakes received 20-30-inch slot length limits in 1991. Regulations in these lakes were in effect through 2005 or 2006. Reference lakes for these four ecological lake classes were fairly common in the three local fisheries management areas represented by the slot limits. As a result, I was able to obtain fisheries data from 18 reference lakes (69-736 acres) with comparable sampling histories (Table 2). Platte and Sullivan lakes, two well-connected central Minnesota lakes, had 24-30-inch slot length limits but results from those lakes were not included in this analysis due to complications from winterkill in one of the basins.

Two different slot length limits were implemented on very large hard-water walleye lakes. These regulations had different goals than did slot limits in smaller lakes. Lake-of-the-Woods (Table 2) is a shared-border water with Canada, the Minnesota portion of 345,000 acres being only about a third of the total lake size. Through the 1980s, the Minnesota portion of Lake-of-the-Woods had a population of very large size northern pike, but the fishery was beginning to attract more effort, harvest, and media attention during the early 1990s. In an effort to preserve the good size structure, a slot length limit protecting 30-40-inch northern pike was enacted in May 1996. Thus, the goal was to protect rather than improve fish sizes. Mille Lacs (Table 2), in contrast, is a 132,516-acre shared fishery between the State of Minnesota and several bands of Chippewa Indians. The fishery is managed with a quota system and the state uses slot length limits to keep northern pike harvests below an annual quota for non-band fishers. Initially, a slot length limit protecting 26-36-inch fish was enacted (May 1998), but the regulation was made more restrictive in 2003 when it was adjusted to 24-36 inches. Two other very large hard-water walleye lakes, Leech (102,948 acres) and Winnibigoshish (58,544 acres) located in north-central Minnesota, were used as reference lakes for Lake-of-the-Woods and Mille Lacs (Table 2). All of these very large lakes are renowned sport fisheries for walleye, but they also support important northern pike fishing.

An additional slot length limit was enacted in Pelican Lake, a large (10,945 acres) lake in the glacial shield area of northeast Minnesota (Table 2). Pelican Lake was judged to have good natural recruitment and lakes of its ecological classification typically have soft water (< 60 mg $CaCO_3$ /l) and a very irregular shoreline. The only reference lake of the same ecological classification near Pelican Lake was Sturgeon Lake (1,664 acres), located in the same fisheries management area.

Finally, I also observed the results of a catch-and-release-only regulation in Steiger Lake, a 158-acre lake in the Minneapolis

Table 2. Ecological lake class, lake dimensions, and Secchi depth measurements for lakes with slot length limits or catch-and-release regulations for northern pike (shaded), and comparable information for reference lakes.

Lake	Ecological classification	Surface area (acres)	Percent littoral area	Maximum depth (ft)	Secchi depth (ft)	Regulation Slot Length	Regulation Start date
				Slot Length Limits on Moderate Size North-central Lakes			
Coon-Sandwick	35	627	80	36	9.0	20-30 inch	1991
Medicine	29	446	69	44	7.0	22-30 inch	1989
North Twin	23	313	44	59	14.0	22-30 inch	1989
Sissabagamah	29	365	60	37	6.5	20-30 inch	1991
Wilkins	31	372	28	39	13.8	20-30 inch	1991
Bagley	29	94	53	39	12.0	Reference	
Beauty	29	217	70	31	7.2	Reference	
Big Bag	35	380	83	17	11.0	Reference	
Big Island	35	238	85	42	12.5	Reference	
Big Sand	35	736	86	23	9.5	Reference	
French	31	137	45	37	4.5	Reference	
Grant	23	208	41	92	12.5	Reference	
Hanging Kettle	31	302	47	35	6.5	Reference	
Hay	29	106	54	32	6.5	Reference	
Julia	31	450	37	43	11.0	Reference	
Lake-of-Isles	32	69	75	48	5.5	Reference	
Little Split Hand	29	223	63	25	11.0	Reference	
Round	31	186	35	52	7.0	Reference	
Ruby	23	235	38	88	21.0	Reference	
Sandy	29	260	77	32	5.3	Reference	
South Twin	23	205	37	45	13.5	Reference	
Sugar	29	416	64	45	12.5	Reference	
Vanduse	35	230	82	27	10.0	Reference	
				Slot Length Limit on a Soft-water Glacial Shield Lake			
Pelican	7	10,945	54	38	9.5	24-32 inch	1998
Sturgeon	7	1,664	0	80	11.0	Reference	
				Slot Length Limits on Large Hard-water Walleye Lakes			
Lake-of-the-Woods	26	344,783	23	36	3.3	30-40 inch	1996
Mille Lacs	26	132,516	25	42	9.0	24-36 inch	1998
Leech	26	102,948	56	150	9.2	Reference	
Winnibigoshish	26	58,544	32	70	8.5	Reference	
				Catch-and-Release on an Urban Lake			
Steiger	24	158	65	37	3.2	Catch-and-release only	1988

metropolitan area (Table 2). Eight reference lakes were compared with this catch-and-release regulation lake. These reference populations were the same lakes used in comparisons with the populations under minimum length limits (Table 1) except that the time periods were shifted to account for a different regulation start date.

Methods

Gill Netting

Minnesota's rich tradition of standardized fish population sampling was critical to this analysis. Multimesh experimental gill nets are one of our oldest standardized sampling tools and their use in sampling northern pike dates back to the 1940s. The experimental gill nets are 250 ft long and consist of five panels (50 ft × 6 ft) with graded bar mesh sizes of 0.75-, 1.0-, 1.25-, 1.5-, and 2.0-inch multifilament nylon, and size selectivity of these nets was previously described by Pierce et al. (1994). Gill nets are set in the morning and lifted the following morning.

Long-term sampling frequency for each lake has been dependent on the lake's size and importance to recreational fishing. For this study, lakes larger than 1,000 acres were sampled every 1-5 years but the interval between samples for lakes smaller than 500 acres was sometimes as long as 10 years. Gill netting occurred from the end of June through August with sampling dates for individual lakes repeated as closely as possible each year (usually within the same calendar week). In each lake, the historical sampling stations were intended to represent important habitats except deep water with low hypolimnetic dissolved oxygen.

Since 1993, the number of gill-net sets used in each lake has been standardized by lake size with more nets used in larger lakes. Up to 6 experimental nets were set in lakes up to 300 acres, 9 nets in lakes up to 600 acres, 12 nets in lakes up to 1,500 acres, and 15 or more nets in lakes over 1,500 acres. Prior to 1993, numbers of net sets were also dependent on lake size, but were sometimes lower and varied somewhat among fisheries management areas. Catch rates from gill nets (i.e. numbers of northern pike per overnight experimental net set; CPUE) were used to track changes in abundance over time within individual lakes. Gill-net catch rates of northern pike have correlated with population estimates, and the utility of catch rates for monitoring changes in relative abundance within a lake was previously described by Moyle (1950) and Pierce and Tomcko (2003a).

Ice-out Trap Netting

Ice-out trap netting when northern pike were staging for spawning, primarily during April, was used as a second method for sampling. Ice-out trapping was useful for capturing large numbers of northern pike, but, unfortunately, trap-net catch rates have not been useful indices of abundance because they have not correlated with population estimates (MNDNR file data, Grand Rapids). Therefore, trap netting was only used to measure size structure of the northern pike populations. Trap nets were 0.75- or 1.0-inch bar mesh and each trap had two throats, a 3-ft × 6-ft rectangular frame opening into the trap, and a 40-ft lead that extended into shore. Ice-out trapping was considered specialized sampling and not part of standard fish surveys. As a result, long-term pre-regulation data were not available to contrast with post-regulation data because ice-out trapping prior to the regulations consisted of only 1-3 consecutive years of sampling. An exception was Mille Lacs, which had 6 years of pre-regulation trapping data. Ice-out trapping was used in all regulation lakes but in only seven of the reference lakes.

Creel Surveys

Creel surveys were used to identify how recreational fisheries adjusted to experimental regulations. Creel surveys were not useful for determining changes in size structure of the northern pike populations because the regulations affected sizes of fish kept by anglers, and recollections from anglers about sizes of fish they released were subjective. Only a limited amount of creel information was available for regulation lakes included in this study, and even less from reference lakes. Creel survey designs varied somewhat because of differences in lake size, but typically included instantaneous angler counts and angler interviews during daylight hours. In addition, surveys were stratified by season (such as winter and early, middle, and late summer) and by weekdays versus weekends and holidays. If more than one creel survey was available for pre-regulation or post-regulation sampling years in a given lake, a single mean creel survey statistic for that lake and period was used for calculating average creel survey statistics across lakes.

Monitoring Changes in Size Structure

Long-term changes in size structure of the northern pike populations were determined by comparing proportions of fish 24 inches and longer, and fish 30 inches and longer, between pre-regulation and post-regulation periods. For some of the regulations with lower or higher length limits, changes in proportions of northern pike 20 inches and longer or 36 inches and longer were also evaluated. For determining the influence of a regulation in an individual lake, I used a repeated measures analysis that accommodated within-year correlations in the binary size structure data (Fleiss et al. 2003). The analysis relied on AIC_c model selection procedures (Burnham and Anderson 2002) to choose between model m1 that allowed only for year-to-year variation in the proportions of fish in a length group, and model m2 that included a fixed effect of the regulation along with year-to-year variation. A generalized linear mixed effects modeling approach (Bolker et al. 2008; Laplace approximation) using the "lmer" function (Bates et al. 2008) in the statistical software package "R" (R Development Core Team 2008) was used to fit models m1 and m2. If calculated AIC_c was lower for model m2 (with a regulation effect), then the length regulation was judged to have influenced the proportion of northern pike in a length class. A difference in AIC_c (Δ_i from Burnham and Anderson 2002) $\geq$2 between models m1 and m2 was considered good evidence for a regulation effect, whereas Δ_i <2 provided very weak support for the regulation effect. I did not calculate Akaike weights and evidence ratios (Burnham and Anderson 2002) for each of the analyses, but because only two models were used, weights and evidence ratios could be readily calculated from Δ_i to examine the relative importance of the two models where Δ_i <2. In cases where fewer than 10 fish were gill netted in a particular year, length data from that year were not used.

Pre-regulation periods were all sampling years before the regulations were implemented and post-regulation periods were all sampling years at least 2 years after the regulations were implemented (Tables 3, 4, and 5). The same time periods were used for reference lakes (Tables 3, 4, and 5). Confidence limits for proportions of fish in each size category were calculated with a quadratic formula (Fleiss et al. 2003) that allowed for non-symmetric confidence limits as proportions approached 0% or 100%.

For maximum, minimum, and slot length limits in small to moderate size lakes, there were enough replicates of regulation and reference populations to draw comparisons between the two. I tested for initial differences between regulation and reference populations during the pre-regulation periods by comparing size structures of the northern pike populations. Non-parametric Wilcoxon rank sum tests were used to compare proportions of fish $\geq$ 24 inches and $\geq$ 30 inches in gill-net catches (pooled across years) at regulation versus reference lakes during the pre-regulation periods. Statistical evaluations of the effectiveness of the regulations compared differences (changes between pre- and post-regulation periods) in the proportions of northern pike in each size class between regulation and reference lakes. Normality of the differences was checked with normal probability plots and Shapiro-Wilk statistics (Zar 1984), then two-sample *t* tests or Wilcoxon rank sum tests were used to test for response differences between regulation versus references lakes. Results were considered significant if P<0.10.

A meta-analysis approach was used to provide an overall assessment of the effectiveness of length-based regulations for changing the size structure of northern pike populations. The approach treated northern pike regulation lakes and their associated reference lakes as four separate experiments: 1) maximum length limit lakes, 2) minimum length limit lakes, 3) slot length limits in moderate size lakes (20-30-inch and 22-30-inch limits), and 4) slot

Table 3. Gill-net catch rates (CPUE) for northern pike, walleye, and yellow perch populations in lakes with maximum length limits for northern pike and reference lakes during pre-regulation and post-regulation sampling years.

			Gill-net CPUE (SE)					
	Sampling years		Northern pike		Walleye		Yellow perch	
Lake	Pre	Post	Pre	Post	Pre	Post	Pre	Post
		Maximum Length Limits						
Andrew	1980,1985,1988,1991,1995	2003,2007	7.3	9.8	15.1	13.3	30.2	24.5
			(2.6)	(5.4)	(2.4)	(1.1)	(3.1)	(10.5)
Big Birch	1981,1986,1991,1995	1999,2003,2007	8.7	8.0	14.2	10.0	20.4	16.7
			(2.2)	(1.4)	(3.3)	(3.5)	(8.9)	(14.2)
Big Swan	1981,1986,1991,1996	2000,2004	12.1	10.8	6.5	5.0	21.2	8.4
			(0.7)	(1.0)	(0.6)	(0)	(5.2)	(1.9)
Burgen	1978,1983,1987,1992,1996	2000,2004	5.3	4.3	1.3	2.0	8.5	0.7
			(1.1)	(1.5)	(0.4)	(1.3)	(3.8)	(0.3)
East Battle	1976,1983,1986,1989,1992,1996	2002,2005	9.5	9.4	9.2	7.7	12.5	1.3
			(0.6)	(2.2)	(1.3)	(1.4)	(4.4)	(0.8)
Green	1979,1982,1986,1990,1991,1992	2002,2003,2004,	3.0	2.5	9.0	6.7	19.5	9.3
	1993,1994,1995,1996	2005	(0.3)	(0.2)	(0.8)	(1.0)	(2.8)	(4.1)
Melissa	1982,1984,1989,1994	2000,2004	10.1	16.5	6.0	7.5	26.7	13.7
			(2.7)	(0.4)	(1.0)	(1.8)	(6.3)	(3.6)
Rachel	1977,1982,1987,1992,1997	2002,2006	5.7	11.3	2.7	2.1	5.3	13.8
			(1.6)	(2.8)	(1.4)	(0.1)	(1.6)	(11.8)
Sallie	1981,1984,1989,1994	2000,2004	10.4	16.4	6.2	15.3	51.8	43.0
			(4.1)	(4.6)	(1.8)	(11.0)	(7.8)	(10.5)
Sturgeon	1979,1982,1986,1991,	2001,2006	10.4	4.9	6.5	2.2	14.1	4.0
			(1.1)	(1.4)	(1.2)	(0.9)	(6.3)	(3.9)
Ten Mile	1978,1983,1988,1991,1994,1995	2000,2003,2006	9.2	8.1	8.4	8.4	15.6	11.6
			(0.8)	(1.2)	(1.1)	(1.0)	(3.3)	(2.2)
		Reference Lakes						
Big Floyd	1981,1986,1991,1996	2001	14.8	24.5	4.0	4.9	10.5	5.3
			(2.6)	(-)	(0.6)	(-)	(4.3)	(-)
Big Pine	1979,1983,1986,1989,1992	1999,2002,2005	4.2	4.6	15.6	22.5	78.6	73.4
			(0.4)	(1.0)	(1.2)	(3.7)	(11.2)	(22.0)
Black Hoof	1979,1984,1989,1994,1995	1999, 2004	11.4	15.1	3.7	6.0	25.9	17.8
			(3.0)	(3.6)	(1.9)	(3.3)	(8.7)	(13.5)
Brophy	1975,1979,1984,1988,1992	2002,2006	13.0	9.0	3.2	2.8	1.1	0.1
			(4.3)	(2.2)	(0.9)	(0.2)	(0.7)	(0.1)
Cotton	1981,1986,1991,1996	2001	8.4	18.9	7.5	9.3	16.5	21.6
			(1.4)	(-)	(2.0)	(-)	(2.4)	(-)
Detroit	1979,1983,1986,1989,1992,1994	2003,2007	11.0	6.9	6.9	4.9	3.1	8.9
			(1.9)	(1.1)	(0.5)	(1.2)	(1.2)	(1.7)
Le Homme	1979,1984,1985,1989,1992	2000,2004	8.6	7.0	6.0	6.3	13.6	1.5
Dieu			(1.6)	(1.8)	(1.7)	(1.2)	(6.0)	(0.6)
Marion	1979,1983,1987,1990,1994	2000,2003,2006	4.4	9.9	5.0	9.6	71.5	18.8
			(1.0)	(1.2)	(0.6)	(1.9)	(10.2)	(1.5)
Minnewaska	1976,1981,1986,1989,1992	2002,2006	2.6	4.2	11.3	9.0	104.4	41.2
			(0.7)	(0.4)	(1.9)	(0.1)	(15.3)	(13.1)
North Lida	1982,1985,1988,1991,1993,1995	2000,2003,2006	3.2	4.7	9.8	11.4	17.2	8.6
			(0.5)	(0.2)	(1.3)	(1.4)	(2.6)	(4.1)
Osakis	1981,1986,1989,1990,1994,1995	2001,2002,2003,	5.0	6.0	14.1	8.3	19.7	5.5
		2006	(0.5)	(0.9)	(1.2)	(1.3)	(5.1)	(2.3)
Pine	1976,1983,1988,1991,1994	1999,2002,2005	3.9	5.3	6.8	6.7	34.2	34.4
Mountain			(0.8)	(1.1)	(1.0)	(1.4)	(6.6)	(14.9)
Rush	1981,1985,1989,1992,1995	2001,2004,2007	3.1	3.2	11.6	10.6	15.9	10.0
			(0.7)	(0.5)	(1.4)	(1.7)	(3.6)	(7.3)
Star	1982,1985,1988,1991,1994	2000,2003,2006	7.4	8.5	6.4	8.4	26.2	23.3
			(1.3)	(1.2)	(0.4)	(1.2)	(7.0)	(7.5)
Steamboat	1980,1985,1990,1993	2000,2003,2006	4.8	5.4	5.9	5.4	38.9	70.3
			(1.0)	(0.4)	(0.9)	(1.0)	(5.1)	(21.2)
Toad	1981,1986,1991,1996	2001,2006	10.3	12.0	14.2	12.6	6.0	2.7
			(1.0)	(5.7)	(1.5)	(3.1)	(2.4)	(0.2)
Washburn	1983,1988,1993	2003	4.0	5.3	2.4	5.3	3.6	1.1
			(0.7)	(-)	(0.3)	(-)	(1.2)	(-)

Table 4. Mean gill-net catch rates (CPUE) and size structure (proportions of fish larger than designated sizes) of northern pike populations in reference lakes and lakes with minimum length limits, slot length limits, and a catch-and-release regulation (shaded), along with sample sizes (n) for the proportions.

Lake	Years sampled Pre	Years sampled Post	Gill-net CPUE (SE) Pre	Gill-net CPUE (SE) Post	Northern pike size structure % ≥ 24 inches Pre	% ≥ 24 inches Post	% ≥ 30 inches Pre	% ≥ 30 inches Post	n Pre	n Post
				Minimum Length Limits						
Kelly-Dudley	1971,1983,1986, 1988,1993,1996	2002,2006	4.7 (0.8)	8.5 (2.3)	11.8	39.2	0.7	2.9	153	102
Reeds	1979,1984,1989, 1996	2002,2006	11.8 7.4)	6.4 (1.4)	10.2	71.9	0.6	12.5	167	64
St. Olaf	1970,1979,1981 1989,1990,1996	2002,2006	0.9 (0.3)	9.0 (0.7)	28.6	50.9	5.7	1.9	35	53
Roemhildts	1983,1985,1987, 1989,1993,1996	2001,2006	3.6 (0.7)	5.0 (0.0)	27.6	25.0	5.2	0.0	58	20
Auburn	1975,1980,1985, 1990,1995	2000,2006	12.1 (4.0)	8.6 (1.6)	14.7	30.1	0.3	3.9	320	103
Bavaria	1975,1980,1985, 1990,1995	2002,2007	6.3 (1.2)	7.4 (4.4)	18.6	37.2	3.2	9.3	156	86
Fish	1973,1978,1982, 1987,1992,1997	2003	3.9 (0.7)	4.6 -	55.7	38.9	11.5	0.0	61	18
Long	1976,1981,1986, 1991,1996	2001,2004, 2006	3.1 (1.1)	7.0 (2.8)	31.2	55.6	1.3	14.3	77	126
Medicine	1976,1981,1986, 1991,1997	2000,2004, 2006	6.5 (0.5)	9.8 (1.7)	25.4	45.1	3.1	9.2	288	348
Minnewashta	1974,1979,1984, 1989,1994	2001,2003, 2007	13.9 (4.1)	19.8 (3.3)	9.9	14.1	2.8	1.9	252	617
Riley	1976,1980,1985, 1990,1995	1999,2005	14.5 (4.5)	9.3 (1.8)	33.9	55.4	8.5	12.5	283	112
Sarah	1976,1981,1986, 1991,1996	2001,2007	14.1 (2.6)	8.8 (1.7)	27.6	62.4	5.4	26.2	388	149
				Slot Length Limits						
Pelican	1977,1980,1986, 1989,1992,1995	2001,2007	10.9 (1.3)	16.1 (6.1)	16.3	29.8	1.3	4.0	762	450
Sturgeon	1975,1979,1984 1990,1995	2002	6.0 (0.7)	4.2 (-)	17.5	22.2	1.2	4.8	331	63
Lake-of-the-Woods	1984-1995	1999-2007	1.6 (0.2)	1.8 (0.1)	57.9	63.2	12.9	21.4	1,012	827
Mille Lacs	1983-1997	2002-2006	1.2 (0.1)	1.4 (0.1)	81.8	87.5	24.3	34.8	581	224
Leech	1983-1995	2000-2006	-	-	22.1	20.3	4.5	3.0	2,152	1,248
Winnibigoshish	1983-1995	2000-2006	-	-	30.5	20.4	2.6	2.8	2,457	1,781
				Catch-and-Release						
					% ≥ 20 inches					
Steiger	1978,1983,1988 2003	1993,1998,	18.3 (5.6)	12.7 (0.9)	60.2	90.4	4.2	8.5	118	188
Auburn	1975,1980,1985,	1990,1995, 2000,2006	8.0 (2.8)	13.4 (4.6)	43.3	72.9	0.8	1.3	120	303
Bavaria	1975,1980,1985,	1990,1995, 2002,2007	5.6 (0.7)	7.4 (2.3)	63.4	67.3	7.0	4.7	71	171
Fish	1973,1978,1982, 1987	1992,1997, 2003	3.9 (0.6)	4.0 (1.3)	87.5	87.2	5.0	12.8	40	39
Long	1976,1981,1986,	1991,1996, 2001,2004, 2006	1.5 (0.1)	6.4 (1.7)	94.7	85.9	5.3	9.8	19	184

Table 4. Continued

Lake	Years sampled Pre	Years sampled Post	Gill-net CPUE (SE) Pre	Gill-net CPUE (SE) Post	Northern pike size structure % ≥ 24 inches Pre	% ≥ 24 inches Post	% ≥ 30 inches Pre	% ≥ 30 inches Post	n Pre	n Post
Medicine	1976,1981,1986,	1991,1997, 2000,2004, 2006	6.3 (0.9)	8.6 (1.2)	58.8	86.6	3.0	7.6	165	471
Minnewashta	1974,1979,1984,	1989,1994, 1998, 2001 2003,2007	10.3 (2.9)	18.8	33.8	44.6	5.2	1.7	77	960
Riley	1976,1980,1985,	1990,1995 1999,2005	15.8 (8.1)	11.0 (1.2)	34.9	82.1	3.0	14.4	166	229
Sarah	1976,1981,1986,	1991,1996, 2001,2007	15.3 (2.7)	10.5 (2.9)	62.2	88.8	4.1	15.9	217	320

Table 5. Gill-net catch rates (CPUE) for northern pike, walleye, and yellow perch populations in reference lakes and moderate size north-central lakes with slot length limits (shaded) for northern pike during pre-regulation and post-regulation sampling years.

Lake	Sampling years Pre	Sampling years Post	Gill-net CPUE (SE) Northern pike Pre	Northern pike Post	Walleye Pre	Walleye Post	Yellow perch Pre	Yellow perch Post
Coon-Sandwick	1976,1979,1984,1990	1995,2000,2005	8.5 (1.5)	9.2 (1.4)	1.3 (0.9)	0.9 (0.1)	8.7 (2.7)	13.3 (1.0)
Medicine	1970,1980,1986,1988	1993,1998,2003	12.0 (2.9)	7.4 (1.1)	5.9 (2.1)	5.3 (1.8)	6.6 (1.6)	14.5 (3.9)
North Twin	1970,1978,1985,1988	1993,1998,2003	10.9 (1.8)	8.9 (0.5)	4.4 (1.2)	4.4 (1.3)	10.2 (1.8)	8.9 (3.6)
Sissabagamah	1980,1986,1989	1994,1999,2004	7.5 (1.0)	6.6 (0.8)	0.9 (0.7)	1.7 (0.3)	1.0 (0.9)	0.4 (0.1)
Wilkins	1977,1985,1989	1994,1999,2004	7.1 (1.4)	6.5 (1.6)	3.8 (1.2)	3.5 (1.0)	1.8 (1.4)	0.7 (0.7)
Bagley	1978,1985	1993,2004	13.5 (1.5)	9.8 (0.5)	0.3 (0.3)	2.3 (1.3)	33.6 (1.4)	18.4 (13.6)
Beauty	1974,1979,1985	1991,1998,2005	4.1 (1.0)	6.4 (1.7)	0.0 (0.0)	4.1 (0.3)	2.4 (2.3)	1.0 (0.6)
Big Bass	1973,1982,1987	1997,2002	11.9 (2.7)	11.6 (0.4)	2.6 (0.5)	4.7 (0.1)	5.7 1.2)	16.0 (3.1)
Big Island	1974,1979,1984	1990,2005	8.8 (1.3)	10.1 (0.9)	0.0 (0.0)	0.3 (0.3)	4.5 (0.6)	4.0 (1.0)
Big Sand	1978,1983,1990	1997,2005	9.1 (0.9)	12.1 (2.4)	2.8 (0.2)	3.3 (0.1)	25.8 (4.6)	24.7 (11.1)
French	1981,1989	1994,1999,2004	4.9 (2.3)	4.2 (1.3)	0.9 (0.3)	1.8 (0.5)	3.0 (2.2)	3.4 (2.4)
Grant	1969,1981,1987	1997,2005	12.8 (1.7)	14.6 (2.2)	0.0 (0.0)	0.2 (0.2)	7.3 (3.4)	4.5 (2.1)
Hanging Kettle	1977,1985,1990	1994,1998,2003	6.1 (2.1)	8.0 (2.6)	3.7 (1.8)	1.8 (0.2)	23.3 (15.2)	29.9 (10.9)
Hay	1980,1989	1994, 2004	8.6 (1.9)	8.4 (0.9)	0.1 (0.1)	0.0 (0.0)	6.2 (4.8)	5.1 (0.6)
Julia	1970,1975,1977,1983,1986 1988	1991,1993,1996, 2003	10.1 (3.3)	7.1 (1.2)	3.9 (1.0)	10.6 (2.4)	61.8 (15.9)	94.2 (16.7)
Lake-of-Isles	1971,1982,1991	1995,2001	7.5 (2.8)	10.1 (0.6)	2.2 (0.8)	2.1 (0.3)	3.7 (1.7)	7.2 (1.3)

Table 5 continued

Lake	Sampling years Pre	Sampling years Post	Gill-net CPUE (SE) Northern pike Pre	Northern pike Post	Walleye Pre	Walleye Post	Yellow perch Pre	Yellow perch Post
Little Split Hand	1975,1980,1985	1991,1996,2004	9.9 (3.3)	11.7 (1.3)	1.0 (0.5)	1.1 (0.3)	30.8 (10.8)	42.0 (14.5)
Round	1985,1990	1994,1999	2.9 (0.8)	4.4 (0.3)	2.3 (0.8)	1.2 (0.0)	3.5 (0.7)	7.5 (4.0)
Ruby	1978,1983,1990	1996,2001,2004	8.9 (1.0)	9.3 (1.1)	2.8 (1.0)	4.4 (1.7)	10.3 (8.7)	4.7 (1.0)
Sandy	1970,1980,1985,1990	1996,2002	13.9 (1.6)	8.9 (3.3)	2.2 (0.6)	4.7 (0.1)	20.8 (6.5)	7.3 (3.7)
South Twin	1981,1987	1995,2000,2004	12.5 (6.9)	17.7 (4.7)	4.0 (0.4)	4.4 (1.1)	72.2 (40.9)	25.9 (1.4)
Sugar	1980,1985	1990,1996	11.1 (1.3)	7.1 (1.6)	2.0 (0.6)	2.9 (0.4)	3.9 (2.9)	4.1 (1.3)
Vanduse	1982,1987	1997,2002	14.6 (2.2)	16.9 (1.4)	0.0 (0.0)	0.0 (0.0)	13.3 (6.7)	5.5 (2.3)

length limits that had upper bounds greater than 30 inches in large lakes (Lake-of-the-Woods, Mille Lacs, and Pelican Lake). The response evaluated across all experiments was the change in proportion of fish ≥ 24 inches. Since only one class of regulation was evaluated (length-based regulations), the meta-analysis was reduced to a comparatively simple calculation of combined effect size for the four experiments using a fixed effects model. Statistical solutions for the model are detailed in Gurevitch and Hedges (1993). In short, effect sizes (d_j) were calculated for each experiment that contrasted regulation and references lakes in relation to a pooled standard deviation of the differences, and a correction for small sample bias. Variances of estimated effect sizes for each experiment (v_j) were used to combine effect sizes across experiments. The cumulated effect size across experiments (d) was an average weighted by reciprocals of the v_j. Confidence intervals for d were constructed from the variance $s^2(d)$, which was the reciprocal of cumulated weights across experiments.

Shorter-term changes in northern pike size structure were evaluated from ice-out trap-net catches. Comparisons of size structure were the same as for gill-net catches except that only 1-3 consecutive years of pre-regulation data were available from regulation lakes, and there were few samples from reference lakes (Table 6). Evaluation of trap-net catches also used repeated measures analyses to identify changes in size structure within each lake.

Monitoring Changes in Abundance

Long-term changes in abundances of northern pike were measured using gill-net catch rates. The average gill-net catch rate each year (CPUE) was considered an independent observation of relative abundance since net surveys were typically about 5 years apart. For maximum, minimum, and slot length limits in small to moderate size lakes, I tested for initial differences between regulation and reference populations during the pre-regulation periods by comparing mean CPUE of the northern pike populations. Non-parametric Wilcoxon rank sum tests were used to compare mean gill-net CPUEs from regulation versus reference lakes during the pre-regulation periods. In individual lakes, CPUEs from pre-regulation years were compared with post-regulation years allowing at least 2 years lag time after the regulations were implemented. The difference between mean CPUE post-regulation and mean CPUE pre-regulation was considered the change in relative abundance of northern pike for each lake. To test for effects of the regulations, changes in relative abundances for regulation lakes were compared with changes for reference lakes using non-parametric Wilcoxon rank sum tests. To examine the relationship between changes in proportions of gill-netted northern pike ≥ 24 inches and changes in CPUE among lakes,

Table 6. Size structure and sample sizes (n) for northern pike caught during ice-out trap netting from reference lakes and lakes with maximum length limits for northern pike during pre-regulation and post-regulation periods. Size structure for northern pike populations was described as proportions of trapped fish that were ≥24 inches and proportions that were ≥30 inches. Included are comparable data from lakes with minimum length limits and from very large walleye lakes with slot length limits for northern pike.

	Years Sampled		% ≥ 24 inches		% ≥ 30 inches		n	
Lake	Pre	Post	Pre	Post	Pre	Post	Pre	Post
		Maximum Length Limits						
Andrew	1994,1995,1996,1997	2001,2003,2004,2006	5.2	12.7	0.7	1.3	712	973
Big Birch	1993,1994,1996	2001,2003,2005,2007	14.6	14.4	0.4	2.1	465	2,680
Big Swan	1993,1994,1995,1997	2001,2003,2005,2007	12.8	36.3	1.9	9.6	740	658
Burgen	1995,1996,1997	2002,2004,2005	16.5	19.0	4.0	3.7	520	347
East Battle	1994,1995,1996	2000,2004,2006	3.3	2.2	0.6	0.3	672	720
Green	1994,1995,1996,1997	2001,2005,2006	24.3	43.8	4.5	11.7	2,323	1,527
Melissa	1997	2003,2006,2007	17.6	35.0	0.5	3.3	193	394
Rachel	1995,1996,1997	2002,2003,2005,2006	8.5	28.0	1.6	3.1	386	574
Sallie	1997	2004,2006,2007	59.5	73.0	7.4	11.1	215	189
Sturgeon	1994,1995	2002,2004,2005,2006,2007	4.6	8.2	0.7	2.9	564	2,776
Ten Mile	1994,1995,1997	2005,2007	13.1	22.1	1.2	2.9	723	375
		Reference Lakes for Maximum Length Limits						
Black Hoof	1995,1996	1999,2001,2003	8.3	6.7	2.2	1.0	360	521
Detroit	1995,1996	2001,2003,2005,2007	3.2	10.1	0.0	0.7	279	417
Star	1994,1995,1996	2000,2002,2004,2006	5.6	1.7	0.3	0.0	320	474
Toad	1994,1995,1996	2000,2002,2004,2006	4.5	12.6	0.0	0.2	553	476
Washburn	1994,1995	2000,2002,2004,2006	3.3	1.5	0.6	0.3	478	791
		Minimum Length Limits						
Kelly-Dudley	1996,1997,1998	2004,2005,2006	8.1	16.9	0.6	0.0	161	178
Reeds	1996,1997,1998	2004,2005,2006	20.5	36.1	1.4	1.4	73	144
St. Olaf	1996,1997,1998	2004,2005,2006	3.5	41.0	0.5	4.6	425	346
		Slot Length Limits on Large Walleye Lakes						
Lake-of-the-Woods	1995,1996	2001,2002,2003,2005	33.6	43.3	11.1	22.0	3,430	6,013
Mille Lacs	1992-1998	2005,2006	49.6	67.4	17.7	28.8	13,155	12,261

information was pooled across all regulation lakes except the two very large hard-water lakes (Lake-of-the-Woods and Mille Lacs, which had different regulation goals).

Fish Community Interactions

Gill-net catch rate data were also obtained for walleye and yellow perch in regulation and reference lakes for the experiments with slot length limits (moderate size lakes) and maximum length limits. The catch rate data were used to determine if changes in abundances of walleye and yellow perch were related to changes in the northern pike populations. Catch rates were obtained in the same years that northern pike were collected (Tables 3 and 5) and catch rates for these species received the same statistical treatment as northern pike catch rates. I also tested to see if consistent shifts in sizes of yellow perch, a preferred prey species, could be related to changes in the northern pike populations. Information about changes in size structure of the yellow perch populations was obtained during the maximum length limit experiment. The response monitored was the proportion of yellow perch ≥ 8 inches in pre-regulation versus post-regulation periods from both regulation and reference lakes. Statistically, these data were treated the same as northern pike size structure data.

Results

Maximum Length Limits

Maximum length limits generally improved the size structure of northern pike populations by increasing proportions of large fish. Compared with reference populations, significant long-term increases were observed in percentages of northern pike ≥ 24 inches (t=2.92; df=14.8; P=0.01) and percentages of northern pike ≥ 30 inches (t=3.37; df=13.5; P<0.01) in gill-net catches from regulation lakes (Figure 1). Normal probability plots and Shapiro-Wilk statistics indicated that differences between pre- and post-regulation size distributions were normally distributed (all regulation and reference lakes were included). The average increase in percentage of fish ≥ 24 inches was 18% in maximum length limit lakes compared with 2% in reference lakes. Not all of the regulation lakes responded that well, however, as there was a broad range of responses. The changes in percentage of fish ≥ 24 inches ranged from a decline of 3% in Burgen Lake to a surprisingly large increase of 50% in Lake Sallie (Table 7). Of the 11 regulation lakes, Andrew, Burgen, and East Battle lakes showed no increase in percentage of fish ≥ 24 inches in the repeated measures analysis (AIC_c for model m1 was lower than m2). The Δ_i for Big Birch and Rachel lakes were only 0.4 and 1.8 respectively, but Δ_i ranged from 2.3 to 14.4 in the other lakes.

The average increase in percentage of northern pike ≥ 30 inches was 5.1% in regulation populations compared with 0.7% in reference populations. In regulation lakes, the responses varied from a decline of 0.1% of the catch being ≥ 30 inches to an increase of 13.1%. Repeated measures analysis for four of the regulation lakes (Burgen, East Battle, Sallie, and Ten Mile) did not indicate an increase in percentage of pike ≥ 30 inches. The Δ_i for Andrew Lake was only 0.1, but other lakes had Δ_i from 4.1 to 9.5. Comparisons of regulation and reference populations during the pre-regulation period suggested no significant difference in percentages of northern pike ≥ 24 inches (Wilcoxon rank sum test P=0.41) or percentages ≥ 30 inches (P=0.12).

Shorter-term improvements in northern pike size structure were also noted from ice-out trap-net catches in lakes with maximum length limits. Differences between pre- and post-regulation samples were not always normally distributed, so Wilcoxon rank sum tests were used to compare regulation and reference populations. The tests indicated significant increases in percentages of northern pike ≥ 24 inches (P=0.04) and also for fish ≥ 30 inches (P=0.01). The median increase in percent ≥ 24 inches in regulation lakes was 9% (range of –1% to 24%) compared with a decline of 2% (range of –4% to 8%) in reference lakes (Table 6). The median increase in percent ≥ 30 inches was 1.7% (range of –0.3% to 7.7%) in regulation lakes compared with a decline of 0.3% (range of –1.3% to 0.7%) in reference lakes (Table 6).

Northern pike relative abundance did not appear to change as a response to the maximum length limits. Pre-regulation differences in gill-net CPUE were not evident between reference and regulation populations (Wilcoxon rank sum test P=0.28). Nor were consistent increases or decreases in gill-net mean CPUE observed after the regulations were enacted and contrasted with CPUE changes in the reference lakes (Wilcoxon rank sum test P=0.42). Changes in mean CPUE ranged from –5.5 to 6.4 fish/net in regulation lakes, and –4.1 to 10.5 fish/net in reference lakes (Table 3). The median change in regulation lakes was a decline of 0.5 fish/net whereas the median change in reference lakes was an increase of 1.3 fish/net.

Minimum Length Limits

Minimum length limits protecting northern pike up to 30 inches long increased the percentages of fish longer than 20 inches and longer than 24 inches, but those improvements did not carry over into fish longer than 30 inches. Long-term analyses of gill-net catches showed increases in percentages of northern pike ≥ 20 inches in all three lakes.

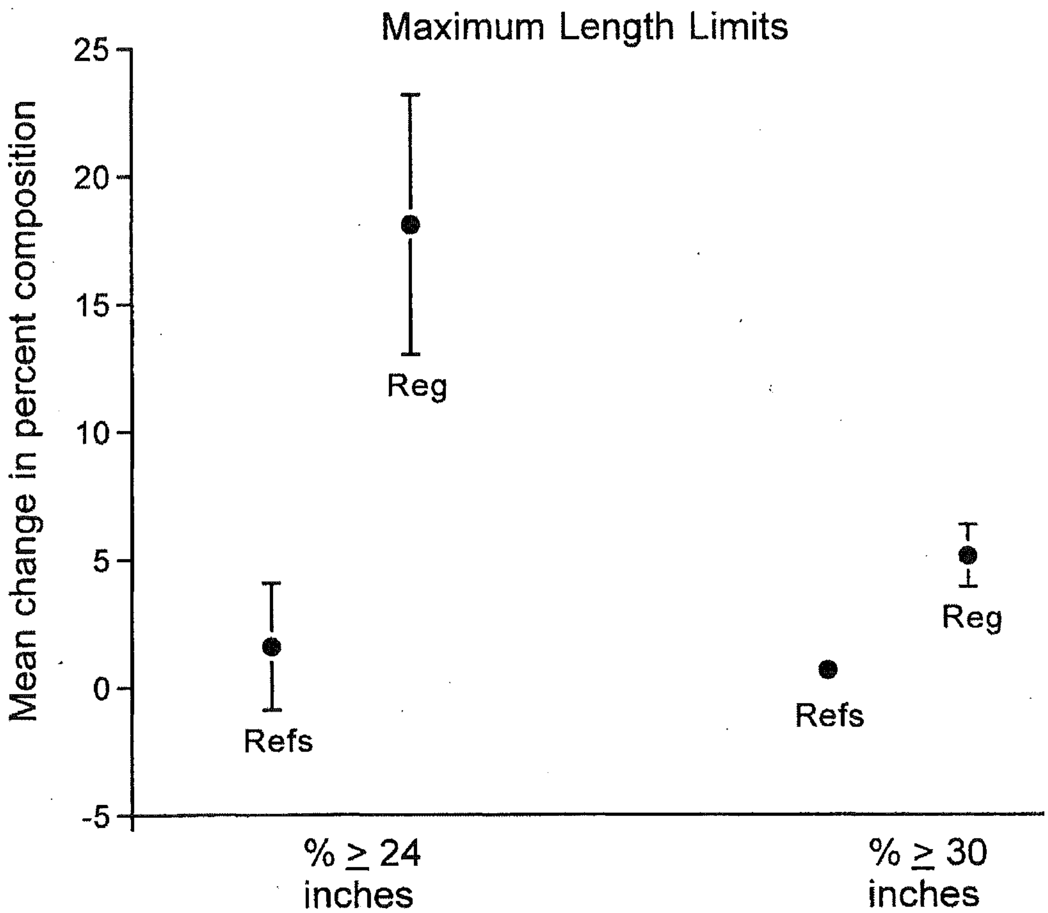

Figure 1. Mean changes (± 1 SE) between pre- and post-regulation periods in percentages of northern pike ≥ 24 inches and ≥ 30 inches in lakes with maximum length limits for northern pike (labeled as Reg in the figure) and associated reference lakes (labeled as Refs). Data were from gill-net surveys.

Table 7. Size structure and sample sizes (n) for northern pike and yellow perch in gill-net catches from reference lakes and lakes with maximum length regulations for northern pike during pre-regulation and post-regulation periods. Size structure for northern pike populations was described as proportions of captured northern pike that were ≥ 24 inches and proportions that were ≥ 30 inches. Size structure for yellow perch populations was described as proportions of fish ≥ 8 inches.

	Northern pike						Yellow perch			
	% ≥ 24 inches		% ≥ 30 inches		n		% ≥ 8 inches		n	
Lake	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Maximum Length Limits										
Andrew	7.0	11.5	0.6	2.1	344	235	11.3	14.8	870	411
Big Birch	12.8	23.7	1.0	3.9	517	355	12.2	1.9	566	750
Big Swan	11.2	43.5	0.8	9.0	509	255	9.3	2.0	431	203
Burgen	12.3	9.6	0.7	3.2	146	52	8.9	62.5	316	8
East Battle	4.8	3.6	0.2	0.7	604	279	45.1	13.2	649	38
Green	21.5	59.7	4.9	18.0	344	139	10.6	4.7	2,260	446
Melissa	14.2	38.5	2.2	11.4	324	431	3.7	0.7	517	307
Rachel	13.8	32.0	1.3	6.9	152	203	3.4	0.0	175	248
Sallie	15.7	66.1	3.3	7.9	210	392	15.1	3.1	720	739
Sturgeon	5.6	21.4	1.3	8.9	395	112	7.0	1.1	316	87
Ten Mile	12.5	20.6	1.4	1.4	625	291	17.6	20.9	646	417
Reference lakes										
Big Floyd	7.0	15.4	2.1	3.6	386	195	31.0	11.9	281	42
Big Pine	31.8	39.7	7.3	9.6	192	209	20.1	10.7	657	3,302
Black Hoof	18.5	2.4	0.6	0.0	168	125	5.9	8.3	288	120
Brophy	5.5	12.0	0.0	0.0	235	108	4.5	0.0	22	1
Cotton	7.3	5.8	1.3	2.2	315	226	41.1	13.6	633	258
Detroit	6.9	20.2	0.7	1.9	692	208	7.7	9.4	286	266
Le Homme Dieu	19.7	31.0	3.1	4.2	421	168	12.4	5.6	574	36
Marion	32.3	15.8	1.6	2.3	248	444	8.7	6.2	829	846
Minnewaska	31.4	25.2	5.4	11.8	223	127	14.0	32.0	4,604	1,236
North Lida	18.0	20.8	2.9	4.2	245	212	3.7	3.4	912	386
Osakis	13.3	18.5	1.7	2.5	420	362	14.8	23.1	1,622	333
Pine Mountain	23.7	22.7	5.8	4.9	190	203	9.4	6.0	785	1,425
Rush	12.0	4.1	1.8	0.7	166	145	10.8	4.0	710	448
Star	10.5	5.2	2.9	1.3	545	381	17.2	7.6	951	1,047
Steamboat	19.2	42.3	5.5	8.3	219	241	24.8	5.6	767	3,165
Toad	7.1	8.8	1.2	0.7	254	307	14.1	4.1	220	74
Washburn	6.1	7.6	3.0	0.0	132	79	4.2	17.6	120	17

Percentages of fish ≥ 20 inches increased from 43% to 85% (Δ_i =14.1) in Kelly-Dudley Lake, from 44% to 92% (Δ_i =1.2) in Reeds Lake, and 69% to 98% (Δ_i =3.2) in St. Olaf Lake. Percentages of fish ≥ 24 inches in gill-net catches (Table 4) showed increases following regulation in Kelly-Dudley Lake (12% to 39%; Δ_i =7.2), Reeds Lake (10% to 72%; Δ_i =2.1), and St. Olaf Lake (29% to 51%; Δ_i =6.9). None of these lakes showed evidence of increasing percentages of fish ≥ 30 inches from the repeated measures analysis.

Shorter-term evaluations using ice-out trapping showed similar results. All three lakes provided some evidence for increases in percentages of northern pike ≥ 20 inches and ≥ 24 inches, but percentages of fish ≥ 30 inches did not necessarily change (Table 6). In Kelly-Dudley Lake, percentages of fish ≥ 20 inches increased from 27% to 53% (Δ_i =1.9), percentages of fish ≥ 24 inches increased from 8% to 17% (Δ_i =1.9), and percentages ≥ 30 inches were 0.6% and 0.0%. In Reeds Lake, percentages of fish ≥ 20 inches increased from 48% to 85% (Δ_i =7.6), percentages ≥ 24 inches from 21% to 36% (Δ_i =1.4), and percentages ≥ 30 inches were 1.4% in both periods. In St. Olaf Lake, percentages of northern pike ≥ 20 inches increased from 10% to 76% (Δ_i =5.7), percentages ≥ 24 inches from 4% to 41% (Δ_i =3.2), and percentages ≥ 30 inches also increased from 0.5% to 4.6% (Δ_i =5.5).

Small sample sizes (i.e. number of years sampled with gill nets; Table 4) perhaps made it difficult to observe any changes in relative abundance that may have resulted from the minimum length limits. Median gill-net CPUEs before and after the regulations were implemented were 4.5 and 8.5 pike/net (Wilcoxon rank sum test *P*=0.29) in Kelly-Dudley Lake, and 5.4 and 6.4 fish/net (*P*=0.80) in Reeds Lake. While only significant at *P*<0.10, there was some evidence of an increase in gill-net CPUE from 0.6 to 9.0 fish/net in St. Olaf Lake (*P*=0.07).

The local reference lake, Roemhildts Lake, did not show the same long-term changes in size structure or gill-net catch rates of northern pike. No differences between periods corresponding to pre- and post-regulation were found in percentages of northern pike ≥ 20 inches, or percentages ≥ 24 inches (Table 4). Repeated measures analysis even provided very weak evidence that percentages of fish ≥ 30 inches may actually have declined in the reference lake (Δ_i =0.2; Table 4). Median CPUEs were 3.0 fish/net pre-regulation and 5.0 fish/net post-regulation (Wilcoxon rank sum test *P*=0.61).

An interesting result from reference lakes in the Minneapolis metropolitan area was that many of the reference northern pike populations showed substantial improvements in size structure (Table 4). For example, changes in proportions of fish ≥ 24 inches ranged from –17% to 35% but averaged 15% (95% confidence interval = 3-28%) among the eight populations. Similarly, average increases were 15% for proportions of fish ≥ 20 inches and 5% for fish ≥ 30 inches. During the pre-regulation period, proportions of northern pike ≥ 24 inches and ≥ 30 inches were not significantly different between regulation and reference populations (Wilcoxon rank sum tests *P*=0.35-0.48).

In spite of the increases observed in reference lakes, the 30-inch minimum length limits still performed fairly well until fish exceeded 30 inches. When the eight reference lakes from the Minneapolis metropolitan area were included with Roemhildts Lake in the analysis, the regulation lakes still showed some improvements in size structure compared with the reference lakes (Figure 2). The average increase in proportion of northern pike ≥ 20 inches was 40% compared with an average increase of 13% among reference lakes (*t*=-2.82; df=10; *P*=0.02). Although only significant at *P*<0.10, the increase in proportions of northern pike ≥ 24 inches (mean = 37%) also tended to be greater than the average increase across reference lakes (mean = 13%; *t*=-2.11; df=10; *P*=0.06). No significant difference was observed between regulation and reference lakes in changes in proportions of fish ≥ 30 inches (*t*=0.79; df=10; P=0.79). Altered size structure did not translate into changes in relative abundance of northern pike as changes in gill-net CPUE did not differ between regulation and reference lakes (Table 4; Wilcoxon rank sum test *P*=0.86). Nor were differences in CPUE apparent between regulation and reference lakes during the pre-regulation period (Wilcoxon rank sum test *P*=0.37).

Slot Length Limits in Moderate Size Lakes

Slot length limits in moderate size lakes in north-central Minnesota produced results that were more difficult to interpret. Three of the five regulation lakes showed large improvements in size structure of their northern pike populations during the long-term gill-net sampling (Figure 3). Proportions of northern pike ≥ 20 inches increased from 14% to 56% (Δ_i =12.7) in Medicine Lake, from 27% to 58% (Δ_i =3.5) in North Twin Lake, and from 20% to 47% (Δ_i =1.2) in Coon-Sandwick Lake (Table 8). Proportions of fish ≥ 24 inches increased from 3% to 19% (Δ_i =13.2) in Medicine Lake, from 12% to 26% (Δ_i =1.6) in North Twin Lake, and from 11% to 23% (Δ_i =3.0) in Coon-Sandwick Lake . Evidence of an increase from 16% to 28% of fish ≥ 20 inches (Δ_i =1.7) was found in Lake Sissabagamah (Table 8),

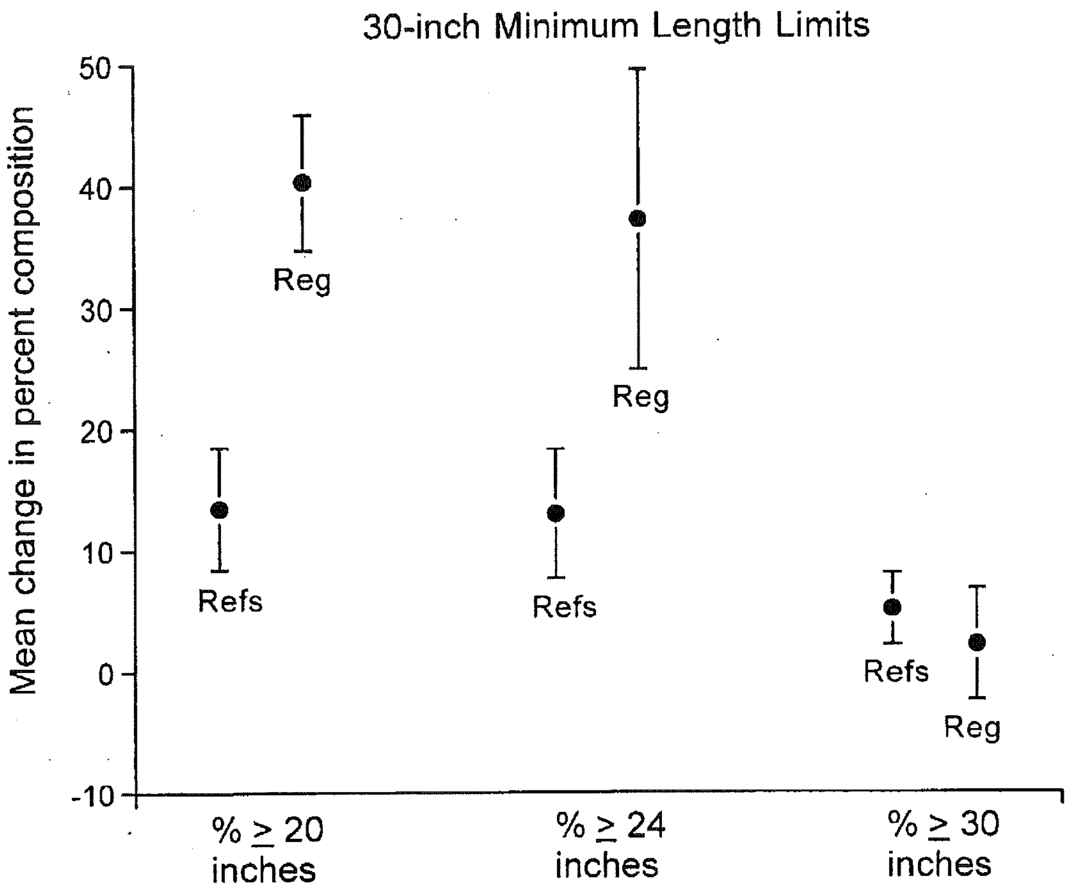

Figure 2. Mean changes (± 1 SE) between pre- and post-regulation periods in percentages of northern pike ≥ 20 inches, ≥ 24 inches, and ≥ 30 inches in lakes with 30-inch minimum length limits for northern pike (labeled as Reg in the figure) and associated reference lakes (labeled as Refs). Data were from gill-net surveys.

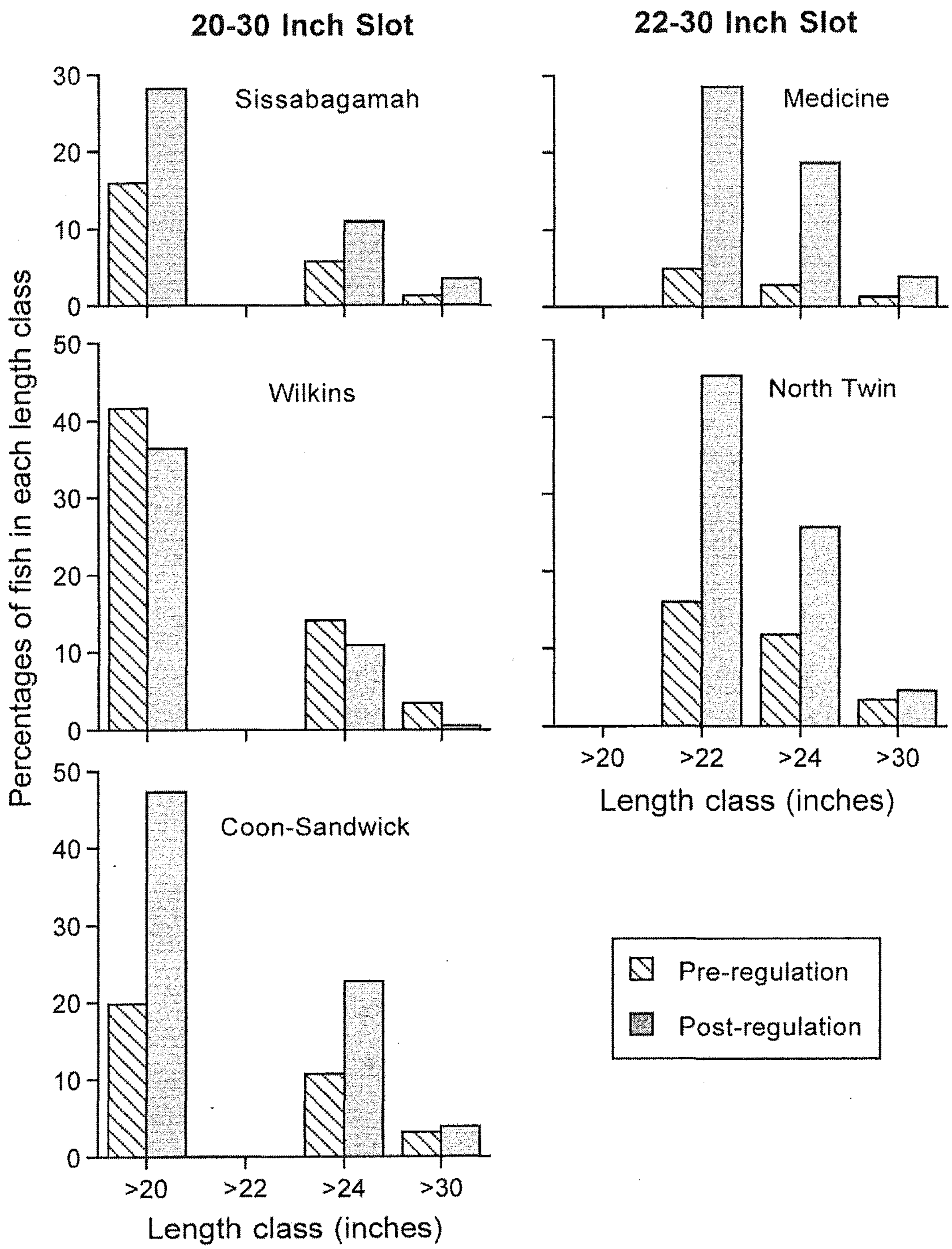

Figure 3. Pre-regulation versus post-regulation percentages of northern pike ≥ 20 inches or ≥ 22 inches, ≥ 24 inches, and ≥ 30 inches in moderate size north-central Minnesota lakes that had 20-30-inch or 22-30-inch protected slot length limits for northern pike. Data were from gill-net surveys.

Table 8. Size structure and sample sizes (n) for northern pike caught with gill nets from reference lakes and moderate size north-central Minnesota lakes with slot length limits for northern pike during pre-regulation and post-regulation periods. Size structure for northern pike populations was described as proportions of fish that were ≥20 inches and ≥30 inches.

	% ≥ 20inches		% ≥ 30 inches		n	
Lake	Pre	Post	Pre	Post	Pre	Post
			Slot Length Limits at Moderate Size Lakes			
Coon-Sandwick	19.8	47.3	3.1	3.9	318	330
Medicine	14.3	56.0	1.2	3.8	322	182
North Twin	27.1	58.4	3.3	4.5	332	245
Sissabagamah	15.9	28.2	1.3	3.4	157	174
Wilkins	41.6	36.4	3.4	0.5	149	184
			Reference Lakes			
Bagley	29.6	23.0	1.9	1.1	108	87
Beauty	29.1	29.7	1.8	2.7	55	111
Big Bass	39.3	68.3	5.5	3.8	163	208
Big Island	42.0	66.1	7.1	3.6	112	112
Big Sand	24.8	51.2	0.4	2.3	246	217
French	25.8	38.1	1.5	0.0	66	97
Grant	35.4	47.4	2.4	2.6	209	156
Hanging Kettle	53.7	60.1	0.8	4.2	123	143
Hay	23.2	51.2	0.0	6.1	95	82
Julia	31.9	57.0	1.7	2.5	288	242
Lake-of-Isles	21.8	8.1	1.8	0.0	55	135
Little Split Hand	32.9	56.5	1.8	2.0	164	200
Round	16.7	32.1	0.0	1.9	54	53
Ruby	33.8	56.9	4.5	6.1	133	181
Sandy	67.0	32.7	2.9	5.6	206	107
South Twin	45.3	52.7	7.0	5.0	86	319
Sugar	20.9	25.2	1.4	3.4	139	119
Vanduse	9.0	30.5	3.4	4.4	145	203

but evidence was not found for increasing proportions ≥ 24 inches. The Wilkins Lake northern pike population had much better size structure than other lakes prior to the regulation, with 42% of gill-net catches ≥ 20 inches (compare the panels in Figure 3). After the regulation, no improvements were observed in northern pike size structure in Wilkins Lake. Proportions of northern pike ≥ 30 inches did not improve with these slot length limits (with the possible exception of Medicine Lake; Δ_i =1.4; Table 8). No significant differences in percentages of fish ≥ 24 or ≥ 30 inches were observed between regulation and reference populations during the pre-regulation period (Wilcoxon rank sum tests P=0.15-0.87).

Similar results were obtained from ice-out trap netting where the largest short-term increases in northern pike size structure were from Medicine, North Twin, Coon-Sandwick, and Sissabagamah lakes (Table 9). Increases in proportions of fish ≥ 20 inches were 7% to 36% (Δ_i =5.5) in Medicine Lake, 28% to 46% (Δ_i =4.3) in North Twin Lake, 26% to 55% (Δ_i =1.2) in Coon-Sandwick Lake, and 9% to 21% (Δ_i =7.4) in Lake Sissabagamah. All the northern pike populations except Wilkins Lake showed increases in proportions of fish ≥ 24 inches (Δ_i =2.2-11.1). Lake Sissabagamah had very weak evidence of an increase in the proportion of fish ≥ 30 inches from 0.4% to 1.2% (Δ_i =1.7), but the other lakes had no apparent change (Table 9). Wilkins Lake had no apparent changes in any of the size structure categories.

Table 9. Size structure and sample sizes (n) for northern pike caught during ice-out trap netting from reference lakes and moderate size north-central Minnesota lakes with slot length limits for northern pike during pre-regulation and post-regulation periods. Size structure for northern pike populations was described as proportions of trapped fish that were $\geq$20 inches and proportions that were $\geq$30 inches.

	Years Sampled		% ≥ 20 inches		% ≥ 30 inches		n	
Lake	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Slot Length Limits at Moderate Size Lakes								
Coon-Sandwick	1990	1995,2004,2005	25.7	54.6	1.0	0.7	680	1,225
Medicine	1988	1993,2002,2003	7.0	35.7	0.1	0.3	939	1,693
North Twin	1988	1993,2002,2003	27.9	46.0	1.5	1.2	458	1,086
Sissabagamah	1989	1994,2004	8.7	20.7	0.4	1.2	1,270	859
Wilkins	1989	1994,2004	40.9	41.2	0.8	1.1	714	944
Reference Lakes								
French	1989	1994,2004	33.0	45.3	0.0	1.3	821	972
Julia	1988	1993,2002,2003	48.7	46.1	0.0	1.4	575	1,808

Reference lakes for these slot length limits also showed substantial improvements in northern pike size structure, and the improvements appeared to begin in the 1990s. Reference lakes from the same ecological lake classes and from the same geographic management areas as the slot length limit lakes showed large amounts of variation in northern pike size structure during the long-term gill-net sampling (Table 8). However, across the 18 reference lakes there was an average increase in proportions of northern pike $\geq$ 20 inches of 11% (95% confidence interval = 3% to 20%), and an average increase in proportions of pike $\geq$ 24 inches of 5% (95% confidence interval = 2% to 9%). Corresponding average increases across the five regulation lakes were 22% for fish $\geq$ 20 inches and 14% for fish $\geq$ 24 inches. Increases in Medicine, North Twin, and Coon-Sandwick lakes were well above the confidence intervals for reference lakes. The increases in Lake Sissabagamah were equivalent to the average increase among reference lakes, and the regulation in Wilkins Lake performed poorly compared with increases in the reference lakes. In the final analysis, when results from the five regulation lakes were compared with results from the reference lakes, there were no significant differences between improvements of the two groups (two sample t=0.15-1.17; df=21; P=0.25-0.36 for the various size categories).

Changes in relative abundance of northern pike were not apparent in either the regulation lakes or the reference lakes (Table 5). The average pre-regulation gill-net CPUE across the five regulation lakes was 9.2 fish/net (SE=1.0) compared with a mean post-regulation CPUE of 7.7 fish/net (SE=0.6), with no statistical evidence that this was a significant difference (Wilcoxon signed rank test P=0.49). Across the 18 reference lakes, mean gill-net CPUE during the pre-regulation period was 9.5 fish/net (SE=0.8), and was 9.9 fish/net (SE=0.9) during the post-regulation period (Table 5). In addition, no significant difference was observed in gill-net CPUE between regulation and reference lakes during the pre-regulation period (Wilcoxon rank sum test P=0.60).

Slot Length Limits in Lake-of-the-Woods, Mille Lacs, and Pelican Lake

The slot length limit protecting 30-40-inch northern pike in Lake-of-the-Woods achieved the goal of preventing a decline in fish of those sizes. The proportion of fish $\geq$ 30 inches in long-term gill-net catches actually increased from 13% to 21% (Δ_i=5.4; Table 4) while CPUE remained about the same (Wilcoxon rank sum test P=0.54). Gill-net CPUE during 1984-1995 averaged 1.6 fish/net (SE=0.2) and was 1.8 fish/net (SE=0.1) during

1999-2007 (Table 4). Ice-out trapping data were consistent with the increase in proportion of fish ≥ 30 inches (Δ_i =0.5; Table 6); the increase was particularly evident for female northern pike (Figure 4). One potential concern with the regulation in Lake-of-the-Woods has been that it might focus harvest effort on fish over 40 inches. In fact, a downward trend in proportions of female northern pike ≥ 40 inches (males are seldom over 40 inches) was observed between 1995 and 2000, but a high catch of fish ≥ 40 inches in 2005 confounded that viewpoint (Figure 4).

In Mille Lacs, size structure of the northern pike population has shown some modest improvements even though the 24-36-inch slot limit only affected recreational fishing by non-band anglers, and did not apply to tribal harvests. Gill netting and ice-out trap netting provided some weak evidence for increases in proportions of northern pike ≥ 30 inches following implementation of the regulation (Tables 4 and 6). Proportions of fish ≥ 30 inches increased from 24% to 35% (Δ_i=1.8) in gill-net catches (Table 4) and 18% to 29% (Δ_i =1.2) in trap-net catches (Table 6). Proportions of northern pike ≥ 24 inches were very high in Mille Lacs gill-net catches during both the pre- and post-regulation periods (82%-88%). No significant difference was observed in gill-net catch rates for northern pike between 1983-1997 and 2002-2006 (Wilcoxon Rank Sum Test P=0.46).

Lake Winnibigoshish and Leech Lake, the two other large walleye lakes used as reference lakes, tended to show the opposite trend compared with Lake-of-the-Woods and Mille Lacs, indicating degrading size structures over the same time periods. In Lake Winnibigoshish, proportions of northern pike ≥ 24 inches declined from 31% to 20% (Δ_i =5.8) whereas proportions of fish ≥ 30 inches did not appear to change (2.6% versus 2.8%; Table 4). In Leech Lake, proportions of fish ≥ 24 inches did not appear to change (22% versus 20%) but proportions of fish ≥ 30 inches showed very weak support for a decline from 4.5% to 3.0% (Δ_i =0.2; Table 4). Ice-out trapping data were not obtained for these reference populations.

The slot limit of 24-32 inches in Pelican Lake seemed to improve the size structure of that northern pike population as well. Long-term gill-net sampling showed weak evidence that proportions of fish ≥ 24 inches increased from 16% to 30% (Δ_i =1.4; Table 4) while proportions of fish ≥ 30 inches increased from 1.3% to 4.0% (Δ_i =3.6). Gill-net CPUE averaged 10.9 fish/net (SE=1.3) before the regulation and 16.1 fish/net (SE=6.1) after the regulation. The highest CPUE was 22.2 fish/net in 2007, but because CPUE was highly variable in the 2 years of post-regulation sampling (Table 4), no significant difference was found in gill-net CPUE from pre- versus post-regulation years (Wilcoxon rank sum test P=0.29). No pre-regulation ice-out trapping data were available for Pelican Lake. A comparison of ice-out trapping data from early years of the regulation (1999-2001) versus later years (2006-2007) indicated no differences in proportion of northern pike ≥ 24 inches (20% versus 22%) or ≥ 30 inches (2.5% for both periods). The reference lake, Sturgeon Lake, only showed weak evidence for an increase in northern pike over 30 inches. In Sturgeon Lake, proportions of gill-netted fish ≥ 24 inches were 18% during the pre-regulation period and 22% after the regulation. Proportions of fish ≥ 30 inches were 1.2% during the pre-regulation period and 4.8% after (Δ_i =0.7). Unfortunately, sample sizes of fish during the post-regulation period were relatively small in Sturgeon Lake (Table 4).

Meta-analysis for Length-based Regulations

The meta-analysis suggested that, in general, length-based regulations had a very large effect on northern pike population size structure. Calculated effect sizes (d_j) and variances (v_j) for each group of regulations were d_{max} =1.22 (v_{max} = 0.18) for the maximum length limits, d_{min} = 1.30 (v_{min} = 0.51) for the minimum length limits, d_{mslots} = 0.45 (v_{mslots} = 0.26) for the slot limits in moderate size lakes, and d_{lslots} = 1.37 (v_{lslots} = 0.82) for the slot length limits in large lakes (where the upper bounds of the slot were greater than 30 inches). The cumulated weighted effect size across all four types of length-based regulations was d = 1.01 (s_d = 0.28). The 95% confidence interval

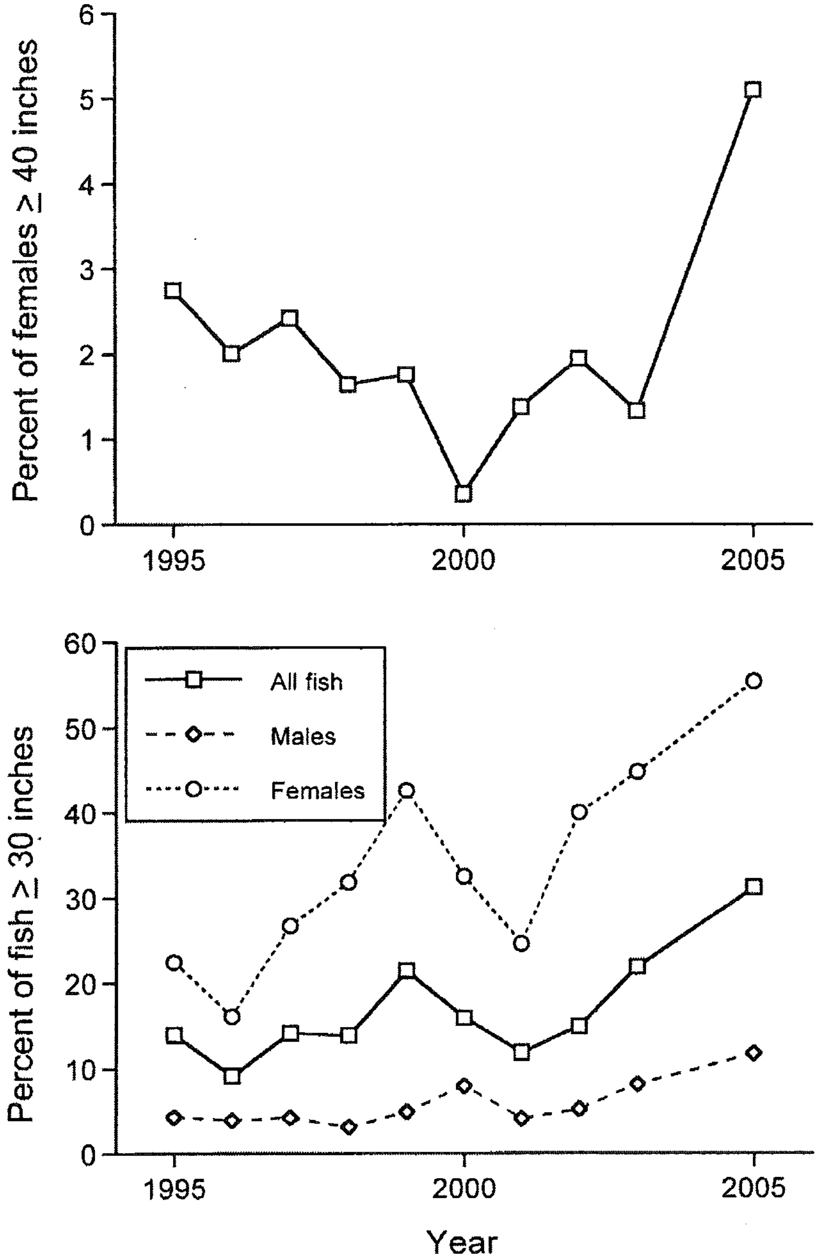

Figure 4. Percentages of northern pike ≥ 30 inches and percentages of female northern pike ≥ 40 inches in ice-out trap-net catches each year from Lake-of-the-Woods.

for *d* was 0.46 to 1.56. In comparison, the conventional interpretation of effect sizes in ecological experiments is that 0.2 is a small effect, 0.5 is a medium effect, 0.8 is large, and effects greater than 1.0 are very large (Gurevitch and Hedges 1993).

Catch-and-Release

The catch-and-release regulation in Steiger Lake produced increases in proportions of intermediate-size northern pike that were equivalent to increases produced by some of the length-based regulations. Increases in proportions of northern pike ≥ 20 inches were found in the gill-net catches. In the case of Steiger Lake, sampling during the first year of the regulation (1988) was included with pre-regulation data to increase sample sizes for pre-regulation information. Proportions of gill-netted fish ≥ 20 inches were 60% during 1978-1988 and 90% during 1993-2003 (Table 4; Δ_i =3.8). Proportions of fish ≥ 24 inches may have also increased from 25% to 60% (Δ_i =0.4), but repeated measures analysis for proportions of fish ≥ 30 inches did not show evidence of a regulation effect (4.2% versus 8.5%). Gill-net catch rates were variable among years (Table 4), and, as a result, did not seem to change significantly. Average gill-net catch rate during 1978-1988 was 18.3 fish/net (SE=5.6) compared with 12.7 fish/net (SE=0.9) during 1993-2003 (Wilcoxon rank sum test P=0.60).

Ice-out trapping during the first 2 years of the regulation also showed some very weak evidence for smaller northern pike size structure compared with later years of regulation. Trapping during 1988-1989 showed proportions of fish ≥ 20 inches to be 72% compared with 88% during 1991-2004 (Δ_i =0.8) and proportions of fish ≥ 30 inches were 4.9% compared with 11.3%; Δ_i =0.5). Repeated measures analysis did not indicate a regulation effect for proportions of fish ≥ 24 inches (31% versus 52%).

Gill-net catches from eight reference lakes in the Minneapolis metropolitan area also showed increases in northern pike size structure, but increases in proportions of fish over 20 and 24 inches seemed to be greater in Steiger Lake than in the references (Table 4). In reference lakes, the average increase in proportion ≥ 20 inches was 17% (95% confidence interval = 1% to 33%) and the average increase in proportion of fish ≥ 24 inches was 12% (95% confidence interval = -1% to 25%). Proportions of large fish ≥ 30 inches also seemed to increase in the reference lakes (mean increase = 4%; 95% confidence interval = 0% to 9%). Meanwhile, gill-net CPUE seemed to decline in Steiger Lake more than in the reference lakes (Table 4). The decline in Steiger Lake between pre- and post-regulation periods was 5.6 fish/net compared with an average increase of 1.7 fish/net in reference lakes (95% confidence interval for the changes in CPUE among reference lakes was –2.3 to 5.6 fish/net).

Creel Survey Statistics

Creel survey statistics placed results from the regulations in the context of the magnitude of fishing effort and harvest rates found in recreational fisheries for northern pike in Minnesota lakes. Estimated annual recreational fishing efforts prior to regulations ranged from 6.6 to 33.9 angler-hrs/acre among six small to moderate size reference lakes (the average among lakes was 21 angler-hrs/acre; Table 10). Corresponding estimates of northern pike harvest ranged from 0.3 to 1.6 fish/acre (0.9 to 3.2 lb/acre) among the reference lakes and the average harvest was 0.9 fish/acre (1.8 lb/acre; Table 10). Among 13 lakes that received maximum or slot length limits, estimated fishing efforts prior to regulation ranged from 8.4 to 37.9 angler-hrs/acre with an average across lakes of 24.5 angler-hrs/acre (Table 10). Estimates of northern pike harvest prior to the regulations were 0.1 to 3.6 fish/acre (0.3 to 4.6 lb/acre) and averaged 1.1 fish/acre (2.2 lb/acre).

Post-regulation creel surveys were obtained at 13 of the lakes, but only 2 were reference lakes. Post-regulation estimates of fishing effort ranged from 5.7 to 34.0 angler-hrs/acre with an average of 16.2 angler-hrs/acre among the 11 regulation lakes (Table 10). Mean decline in fishing effort among the regulation lakes was 8.2 angler-hrs/acre (paired t=-3.76; df=10; P<0.01). For the two reference lakes,

Table 10. Estimates of fishing effort and northern pike harvest from creel surveys at lakes with length regulations for northern pike and reference lakes. Years listed in italics are pre-regulation surveys and years listed in standard font are post-regulation surveys. Years with an asterisk denote creel surveys conducted only during the open-water season. The other creels list cumulative open-water and ice-fishing effort and harvest.

		Fishing effort	Northern pike harvest	
Lake	Year	(angler-hrs/acre)	fish/acre	lbs/acre
		Maximum Length Limits		
Burgen	1995-96	28.8	0.7	1.5
Green	1995-96	19.0	0.3	1.0
	2001*	5.7	0.02	0.04
	2004*	6.9	0.03	0.08
	2005	8.3	0.02	0.08
Melissa	1994-95	23.3	1.7	3.8
	2003-04	12.5	4.1	10.1
Rachel	1995-96	21.5	1.1	2.5
	1996-97	21.6	0.5	0.8
Sallie	1994-95	20.4	0.6	1.5
	2003-04	18.2	3.0	9.0
Sturgeon	1995-96	33.2	1.4	3.3
	2005*	19.4	0.3	0.8
Tenmile	1995*	10.9	0.1	0.4
	1996*	8.4	0.1	0.3
	2005*	6.2	0.01	0.01
	2006	6.1	0.04	0.05
		Slot Length Limits		
Coon-Sandwick	1990-91	37.9	1.0	2.0
	1995-96	25.7	0.4	0.6
	2005*	7.9	0.4	0.7
Medicine	1988-89	32.3	3.6	4.6
	1993-94	28.9	2.5	4.0
	2003-04	16.7	0.8	1.5
North Twin	1988-89	21.7	0.9	3.1
	1993-94	22.3	0.6	1.3
	2003-04	18.7	0.4	0.8
Pelican	1993*	14.3	1.1	2.7
	1994*	13.2	0.9	2.3
	2007*	8.1	0.3	0.6
Sissabagamah	1989-90	35.8	1.7	2.1
	1994-95	27.2	2.5	3.0
	2005*	15.1	0.4	0.5
Wilkins	1989-90	21.7	0.7	1.6
	1994-95	34.0	2.7	4.6
	2005*	17.4	0.1	0.4
		Reference Lakes		
Detroit	1994-95	17.9	1.3	2.7
French	1989-90	32.3	1.4	2.4
	1994-95	30.4	1.7	4.6
	2003*	15.7	1.5	4.0
Julia	1988-89	16.4	1.3	3.0
	1993-94	22.9	1.4	3.4
	2003-04	20.1	0.6	1.1
Minnewaska	1995-96	26.9	1.6	3.2
	1996-97	13.3	0.7	1.9
North Lida	1995-96	10.5	0.6	1.5
	1996-97	6.6	0.3	0.9
Osakis	1995-96	33.9	1.1	2.3
	1996-97	22.4	0.5	1.1

fishing effort averaged 22.3 angler-hrs/acre during the post-regulation period. Estimated post-regulation harvests of northern pike ranged from 0.01 to 4.1 fish/acre (0.01 to 10.1 lb/acre) and averaged 1.2 fish/acre (2.7 lb/acre). Seven of the lakes showed declines in harvests of northern pike (Table 10). In contrast, large increases in harvest were observed at lakes Melissa and Sallie, where both relative abundance and size structure of the northern pike populations had increased. Catch rates in lakes Melissa and Sallie were very high for anglers who were specifically fishing for northern pike; estimated catch rates were 0.8 and 0.6 fish/angler-hr, respectively, and angler-released northern pike longer than 36 inches were recorded for the first time during post-regulation creel surveys.

While compliance with the regulations was high in some lakes, lower compliance rates were also observed in several lakes. From questions asked of anglers during creel survey interviews at lakes Melissa and Sallie, 97% of summer anglers and 66-76% of winter anglers were aware of the 24-inch maximum length regulation and could recite it correctly (Erickson 2005). Creel clerks measured no illegal fish from Lake Melissa and only two illegal fish from Lake Sallie, indicating a high level of compliance with the regulation. In the five moderate size lakes with slot length limits, illegal fish averaged 13% of harvested northern pike measured by creel clerks, and 19% of voluntary tag returns from fish marked with plastic anchor tags during spring 1993-1995 (details provided in Pierce and Tomcko 1998). This level of noncompliance was observed 3-4 years after slot length limits were initiated, but high rates of noncompliance were also observed 10 years later (Moen 2004; Koski 2006). For example, illegal fish were 19.6% of harvested northern pike measured by a creel clerk in Coon-Sandwick Lake during 2005 even though angler awareness of the regulation was relatively good. In Coon-Sandwick Lake 88.3% of anglers interviewed during 2005 were aware of the regulation, and of the aware anglers, 82.2% could recite the regulation correctly (Koski 2006).

Despite high levels of noncompliance in some lakes, exploitation of protected-size fish would have been much greater without regulations, as inferred from reference lakes and regulation lakes prior to enactment of the length limits. Length frequencies of creeled northern pike showed that when regulations were in effect, recreational anglers generally released protected-size fish (Shavlik 2005; Sewell 2006). The magnitude of potential savings in harvests from protective size limits was illustrated at Pelican Lake, where length frequencies of harvested and released fish showed northern pike between 24 and 32 inches composed 31-35% of the harvests during 1993-1994 before the slot length limit was in effect (Table 11; Burri 2008). After the slot length limit was enacted, a 2007 creel census documented only one harvested fish over 24 inches with 20% of released fish in the protected sizes (Table 11). In two of the reference lakes (French and Julia), an average of 57% of harvested northern pike documented in creel surveys and 70% of tag returns were fish of sizes that would have been protected by slot length regulations (Pierce and Tomcko 1998). Creel surveys coupled with tagging studies (Pierce and Tomcko 1997) illustrated how slot length limits significantly reduced exploitation rates of northern pike > 20 inches compared with those two reference lakes.

Fish Community Interactions

Overall changes in the northern pike populations under slot or maximum length limits did not seem to affect walleye and yellow perch populations. One possible exception was that increases in gill-net catch rates for northern pike were correlated with increases in walleye catch rates (r= 0.56; P=0.02; n=16 lakes; Figure 5; Tables 3 and 5). Otherwise, differences between pre- and post-regulation gill-net catch rates for northern pike did not correspond with differences between pre- and post-regulation catch rates of yellow perch (r= -0.07; P=0.78) or changes in proportions of yellow perch $\geq$ 8 inches (r= -0.11; P=0.75; Figure 5; Tables 3, 5, and 7). Nor did changes in the proportions of northern pike $\geq$ 24 inches correlate with differences between pre- and post-regulation catch rates for walleye (r=0.44; P=0.09), catch rates for yellow perch (r= -0.27; P=0.32), or changes in proportions of

Table 11. Length frequency distribution of angler harvested and released northern pike in Pelican Lake, 1993, 1994, and 2007. The gray bar represents sizes of northern pike protected by the slot length limit during 2007.

Length	1993	1994		2007	
(inches)	Harvested	Harvested	Released	Harvested	Released
<6.0			1		17
6.0 - 6.9			9		16
7.0 - 7.9			1		41
8.0 - 8.9			10		21
9.0 - 9.9			8		18
10.0 - 10.9			53		73
11.0 - 11.9			20		14
12.0 - 12.9			162		232
13.0 - 13.9	1		43	2	119
14.0 - 14.9	1	1	173	3	73
15.0 - 15.9	3	2	198	10	159
16.0 - 16.9	5	5	105	7	107
17.0 - 17.9	2	3	39	6	79
18.0 - 18.9	11	14	225	18	78
19.0 - 19.9	17	14	27	15	69
20.0 - 20.9	19	15	94	28	72
21.0 - 21.9	27	27	17	35	38
22.0 - 22.9	26	23	39	46	64
23.0 - 23.9	30	21	19	41	71
24.0 - 24.9	20	6	1	1	119
25.0 - 25.9	21	13	5		73
26.0 - 26.9	15	12	3		65
27.0 - 27.9	9	6	3		25
28.0 - 28.9	4	6	4		34
29.0 - 29.9	4	6	3		8
30.0 - 30.9	2	2	3		13
31.0 - 31.9		2	1		6
32.0 - 32.9	1	3			2
33.0 - 33.9		1			1
34.0 - 34.9		1			
35.0 - 35.9					
36.0 - 36.9					1
Mean Length (inches)	22.8	22.9	15.7	20.7	17.5
n	218	183	1266	212	1,708

yellow perch ≥ 8 inches in the gill-net catches (r= -0.32; P=0.33; Figure 5; Tables 3, 5, and 7).

Enhanced proportions of large northern pike did not appear to constrain northern pike abundance via cannibalism. Changing size structure in the regulated northern pike populations did not cause corresponding trends in relative abundance. Information was pooled across all regulation lakes except the two very large walleye fisheries (Lake-of-the-Woods and Mille Lacs, which had different regulation goals) to compare changes in proportions of gill-netted northern pike ≥ 24 inches and changes in gill-net catch rates (Figure 6). The changes in size structure were not correlated with changes in gill-net catch rates (r=-0.03; P=0.90; n=21 lakes). In all, altered northern pike size structure at levels caused by the regulations produced no trends in northern pike relative abundance that led to predictable fish community changes.

Discussion

Even though regulations did not work in every lake, the broader-scale statewide finding was that length regulations resulted in some

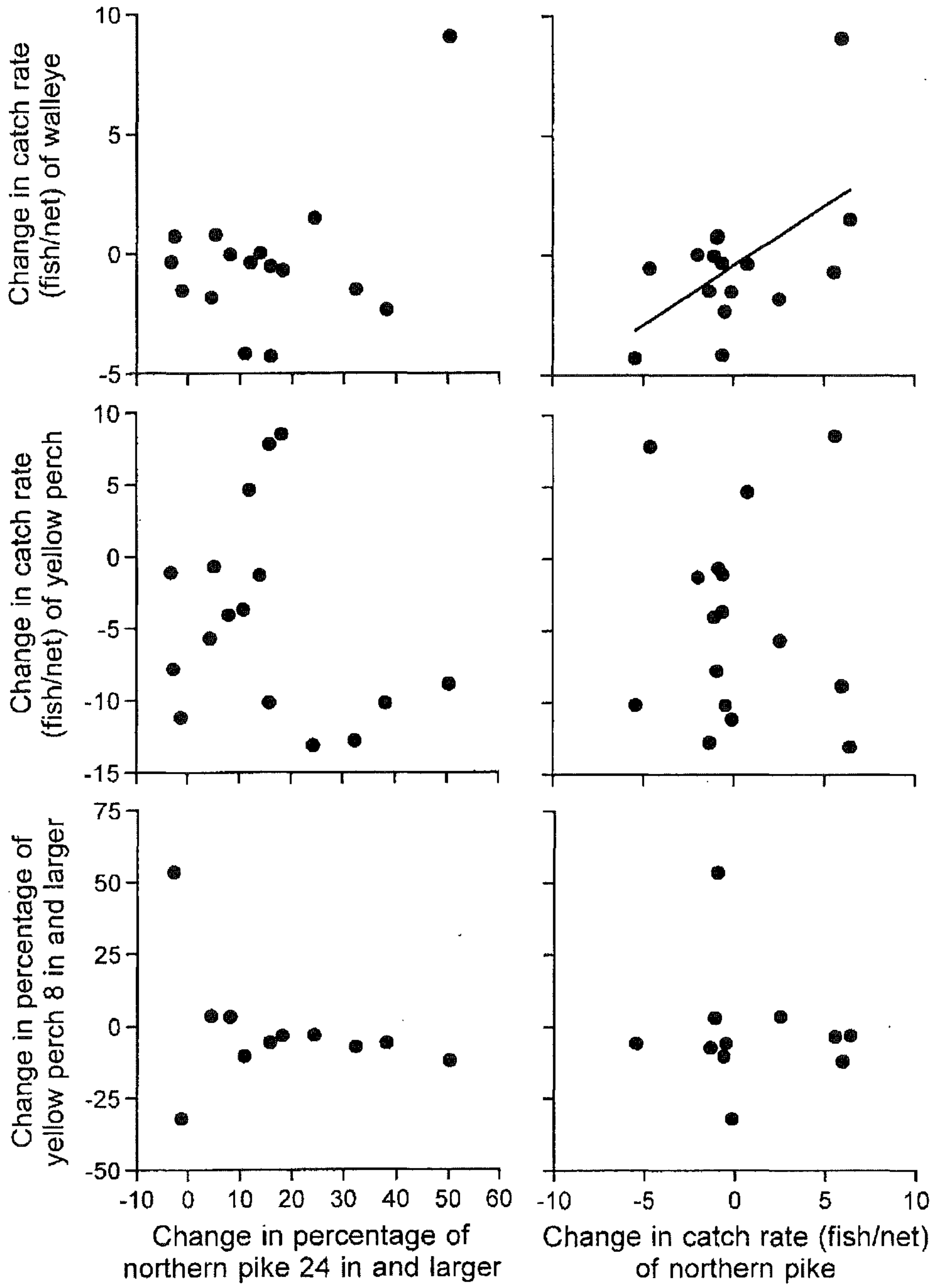

Figure 5. Fish community interactions at lakes with maximum length limits and moderate size lakes with slot length limits for northern pike. Northern pike population metrics were changes between pre- and post-regulation gill-net catch rates and proportions of fish $\geq$ 24 inches in gill-net catches. Walleye and yellow perch population metrics were changes between pre- and post-regulation gill-net catch rates, and for yellow perch, changes in proportions of fish $\geq$ 8 inches in gill-net catches.

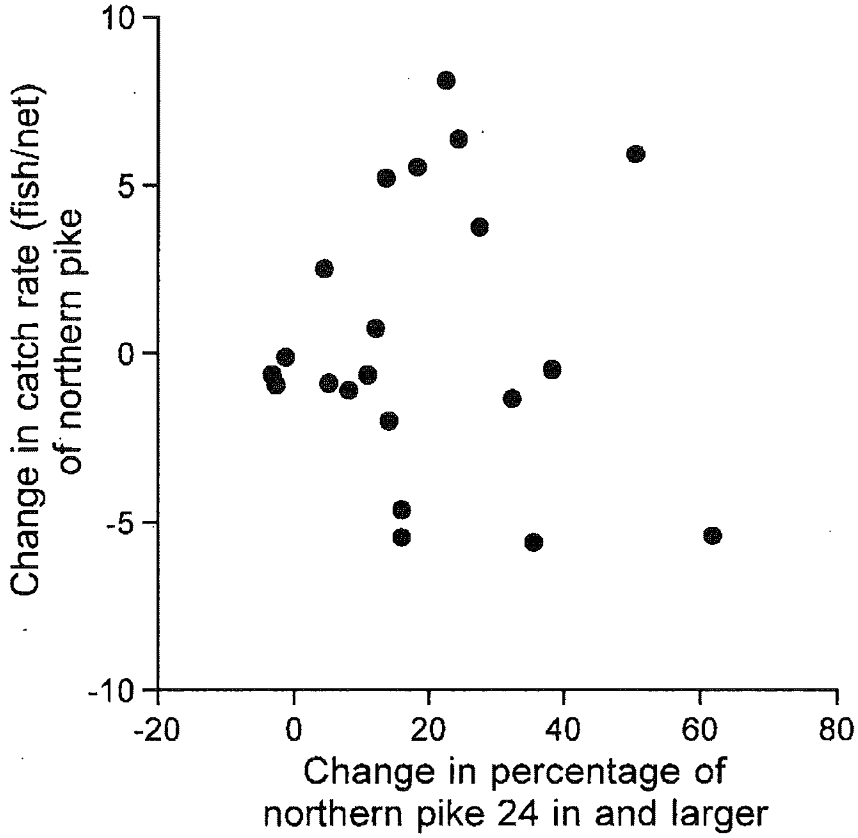

Figure 6. Relationship between changes (from pre- to post-regulation) in northern pike size structure (proportions of gill-netted fish $\geq$ 24 inches) and corresponding changes in gill-net catch rates for northern pike. Data were included from maximum, minimum, slot length limits (except the two very large walleye fisheries that had different regulation objectives) and the catch-and-release regulation (*n*=21 lakes).

significant improvements in the size structure of northern pike populations. The improvements were detected against the backdrop of reference populations that initially appeared to have similar sizes and relative abundances of northern pike. The meta-analysis illustrated that the magnitude of the effect was very large in relation to what might be expected for ecological experiments, and more importantly, the changes were often large enough to be readily noticed by anglers and resort owners. In Medicine Lake, for example, a resort owner informally tracked numbers of large northern pike caught by his clientele. Prior to the regulation, resort guests were catching about one fish over 30 inches each summer. After 7 years of regulation, resort guests were catching (and typically releasing) nearly one fish per week larger than 30 inches. During ice-out trapping prior to the regulation in Medicine Lake, mean length was only 16.5 inches and only 15 fish exceeded 22 inches out of 939 fish sampled. After 14-15 years, mean length had increased to 18.9-19.8 inches and 109 fish exceeded 22 inches out of 918 fish sampled. In lakes Sallie and Melissa, 10 years after the maximum length limits began, walleye anglers were expressing concerns about high numbers of large northern pike potentially impacting walleye populations even though walleye data did not necessarily support their concerns. Regulations in those two lakes were extended for 5 more years to specifically monitor the walleye concerns.

The principal differences between length limits in my study, and some earlier length limits that were not judged to be successful, were the regulations' objectives. Minnesota's length limits were intended to provide larger fish for recreational fisheries whereas objectives for other studies were to promote maximum yields. For example, Latta (1972) used a yield-per-recruit model to judge the effects of changing minimum length limits on yields in typical Michigan fisheries. From field studies, Snow and Beard (1972) concluded that an 18-inch minimum length limit in Bucks Lake, Wisconsin, was not biologically justified because it only served to reduce harvests of sizes of northern pike that already had high natural mortality rates. The length limit in Bucks Lake resulted in an 82% decrease in yield. Similarly, yields were found to decline by 72% under a 22-inch minimum length limit at Escanaba Lake, Wisconsin (Kempinger and Carline 1978).

Length limits in the Minnesota lakes protected northern pike considerably larger than the studies listed in the previous paragraph with the expectation that reduced yields were an acceptable trade-off for producing larger fish. In fact, reduced yields were considered especially important for northern pike over 24 inches that seem to be very vulnerable to over-exploitation (Pierce and Tomcko 2003b). Recreational fishing by all methods tends to select for large northern pike (Pierce et al. 1995; Pierce and Cook 2000). However, large fish are also the least productive part of the population (Pierce and Tomcko 2003b). Secondary production estimates from seven Minnesota lakes indicated that most of the annual production of northern pike occurred at ages 3 or younger and very little of the annual production was from fish ages 6 and older (Pierce and Tomcko 2003b). The average annual production rate for fish ages 2 and older was 3.7 lb/acre/yr whereas the production rate for fish ages 6 and older was only 0.1 lb/acre/yr. This very low production rate for the oldest segment of populations indicates how susceptible large northern pike are to overfishing. Using a 100-acre lake as a hypothetical example, harvest of 10 lb (the equivalent of one 35-inch fish) would deplete the entire annual production of large northern pike for that lake and year. This example illustrates how management aimed at producing large northern pike must severely restrict the harvest of large fish.

Results from this study show that protection of large northern pike seems to have more value than liberalized bag limits for altering northern pike population size structure. Some management efforts to restructure populations consisting of abundant small individuals have focused on removal by trap netting or promoting angler harvest through bag limits more liberal than the statewide (3 fish) limit. Intensive removal of small (< 24 inches) northern pike with trap netting was demonstrated to be ineffective in altering size structure, and creel surveys showed that anglers harvested substantially fewer fish than the trap netting (Goeman et al. 1993). Goeman et al. (1993) concluded that even if anglers could be induced to remove more small northern pike, levels of harvest might still not be enough to alter population size structure.

Results from this study also show the range and magnitude of responses we can reasonably expect from length limits that protect larger-size northern pike. Typical increases in proportions of fish ≥ 24 inches (in gill-net catches after adjusting for changes in the reference populations) were 16% with maximum length limits and 24% with minimum length limits. Improvements in sizes of fish were also observed under the slot length limits at Lake-of-the-Woods and Mille Lacs, even though regulation objectives did not include improving fish sizes. In Lake-of-the-Woods, proportions of northern pike ≥ 30 inches increased by nearly 9% even though the intent of the regulation was simply to maintain the original size structure. Sizes of northern pike in Mille Lacs also improved more than expected considering the slot length limit only affected recreational fishing by non-band anglers. These results provide guidance for future management planning in individual lakes by giving a realistic suite of expectations for length limits, including the possibility that there will be no change in fish sizes.

An important aspect of evaluating length regulations is identifying factors causing the regulations to fail. Unfortunately, no single factor was implicated across all five lakes (Andrew, Burgen, East Battle, Sissabagamah, and Wilkins) where the regulations did not improve size structure compared with reference lakes. Connections allowing fish movement to and from other waters were a potential factor. Lakes allowing the easiest migration of northern pike were Burgen and Wilkins lakes, and Wilkins Lake already had good size structure prior to the slot length limit (Figure 3). East Battle Lake was also connected to other waters, but the area fisheries manager suggested that the extent of the connection was not important for northern pike movement. Nor did other differences in lake habitats consistently affect results. Gill-net catch rates, which give some indication of natural recruitment, averaged 5.3-9.5 fish/net in lakes where regulations failed, but fell within the range of catch rates from other lakes where regulations worked. East Battle Lake was historically known for high recruitment and abundant spawning and nursery habitat. Burgen Lake had the smallest surface acreage used for maximum length limits, but other lakes where regulations failed were within the size range of lakes where regulations worked. Nor did maximum depth or the amount of littoral habitat seem to influence results.

Angler noncompliance was another factor potentially influencing regulation results. Giglioti and Taylor (1990) used a simulation model to predict that effects of noncompliance on legal harvests would vary by fish species, and that illegal northern pike harvests of 20-60% would reduce legal harvests by about 19-47%. In my own work, noncompliance was studied rigorously only in the moderate size lakes with slot length limits (Pierce and Tomcko 1998). Noncompliance was observed first hand in Lake Sissabagamah, and rates of noncompliance in Sissabagamah and Wilkins lakes were relatively high. In those two lakes, 14-19% of fish measured during creel surveys were illegal, and 21-29% of tag returns were illegal fish (Pierce and Tomcko 1998). These rates were not necessarily greater than rates in North Twin and Coon-Sandwick lakes where 6-19% of creeled fish and 14-27% of tag returns were illegal. Medicine Lake had the lowest levels of noncompliance (5-7%; Pierce and Tomcko 1998). Most fishing pressure on Medicine Lake was from a resort where the regulation was actively promoted by the owners and their clients. Building angler support and an understanding of the value of length limits, as witnessed at Medicine Lake, seemed to be as important for compliance as enforcing the regulations.

Conversely, angler noncompliance and hooking mortality rates for released fish were not high enough to prevent length regulations from affecting changes in northern pike size structure in most lakes. Exploitation of protected-size fish was apparently greater in the reference lakes (see Pierce and Tomcko 1998 for examples). Rates of hooking mortality were not measured in this study, but a literature review of previous studies found that average hooking mortality for northern pike was less than 5% (Tomcko 1997). Individual studies covering various fishing methods reported hooking mortality rates of 0-14%, although an exceptionally high rate of 33% was found for pike hooks (also known as Swedish hooks) used in ice fishing (DuBois et al. 1994). Pike hooks were not commonly used for ice fishing in the Minnesota lakes. Telemetry studies with northern pike in a German lake (Klefoth et al. 2008) showed that sublethal catch-and-release impacts on behaviors such as movement and habitat choice were short-term and reversible.

The lack of fish community responses in my study was surprising considering the magnitude of some northern pike population changes, along with previous case studies showing strong links between northern pike predation and community dynamics. For example, availability of yellow perch was likely the most important biotic factor affecting growth rate and body condition of northern pike in Escanaba Lake, Wisconsin (Inskip and Magnuson 1986). Establishment of the northern pike population in Escanaba Lake was considered responsible for higher mortality and reduced numbers of yellow perch (Kempinger and Carline 1978). The fish community in Horseshoe Lake, Minnesota, was influenced for more than 10 years by stocked northern pike (Anderson and Schupp 1986). Predation on 5-6-inch yellow perch nearly eliminated recruitment of yellow perch to adult sizes and appeared to be the major factor causing collapse of the yellow perch population. Reduced growth and abundance of walleye and largemouth bass *Micropterus salmoides* were attributed to the reduction in yellow perch in Horseshoe Lake. Northern pike stocking in Grace Lake, Minnesota, caused large declines in populations of yellow perch and white sucker *Catostomous commersoni* that appeared to affect the walleye population (Wesloh and Olson 1962; Colby et al. 1987). Following extirpation of northern pike and chemical treatments to reduce aquatic vegetation in Lake Harriet, an urban lake in Minneapolis, yellow perch and white sucker increased to high abundances (Colby et al. 1987). Reductions of yellow perch by stocked northern pike in Lake 221 of the Experimental Lakes Area, northwestern Ontario, caused trophic changes large enough to cascade down through the aquatic community (Findlay et al. 1994). The positive relationship between northern pike and walleye catch rates in my study does not seem logical for two species with high potential to compete with each other. A potential explanation is that changes in walleye relative abundance were an artifact of shifting walleye-stocking strategies during the time period of this study. In contrast to my study, Jacobson and Anderson (2007) found a negative effect of pike abundance on walleye abundance in a large-scale analysis of Minnesota lake surveys. Differences between the two studies were that I examined changes in catch rates over time instead of coincident relative abundances, and the Jacobson and Anderson (2007) study only included lakes with poor natural reproduction of walleye.

One hypothesis going into this study was that enhanced numbers of large northern pike would lead to an overall reduction in northern pike density, with large fish exerting some "top-down" control over high numbers of small fish. However, no top-down control was evident in the relationship between changes in northern pike size structure and changes in CPUE among lakes. This result contrasts with apparent density dependence in size structure found among lakes by Pierce et al. (2003). Several European studies have suggested that cannibalism can regulate population density (Kipling and Frost 1970; Grimm 1983; Treasurer et al. 1992), but based on a literature review, Craig (2008) concluded that changes in population density and fish sizes are caused by a complex variety of factors influencing recruitment, growth, and mortality. What is not clear from my study is whether current northern pike densities will be maintained in the face of altered size structure when time scales of protecting large northern pike exceed several decades.

A particular strength of this study compared with similar work was the large number of reference lakes available. Reference lakes demonstrated the amount of variability found among northern pike populations even from lakes of the same ecological classifications. Beginning in the 1990s, and about the time many of these size-based regulations went into effect, there was a general improvement in northern pike sizes in small to moderate size lakes. Reference lakes (for slot length limits) across a large part of north-central Minnesota, as well as Minneapolis metropolitan lakes (references for the minimum length limits), sometimes showed large improvements in fish sizes that did not seem to be linked to any widespread environmental trend during this period. More likely was a change in angling behavior toward more catch-and-release. However, no hard data are available to support this notion and reference lakes used for comparison with maximum length limits (generally larger than 1,000 acres) did not show the same trend. Minnesota is fortunate in having a large freshwater resource that can be used for regulation studies and the meta-analysis, in particular, highlighted the value of large numbers of both reference and regulation lakes.

This study further demonstrated the extended length of time required for evaluating changes in population size structure. A useful example is provided in Figure 7, which tracked mean lengths of northern pike caught during ice-out trapping at Coon-Sandwick Lake. The 15-year evaluation period illustrated in Figure 7 is not unreasonably long considering the life span of individual northern pike in these lakes can reach 11-14 years or longer, and regulations protecting northern pike up to 40 inches might require even longer evaluation periods. Using modern aging techniques, Casselman (1996) reported a northern pike from Lake Athabasca, Saskatchewan, that was 29 years old. Unfortunately, the fishing public tends to demand quicker results that are not well aligned with the life history of longer-lived species like northern pike. Thus, when fisheries managers talk to the fishing public, we need to stress the long time periods needed for evaluating regulations, as well as promoting the substantial value of conserving large fish when the goal is to shift population size structure.

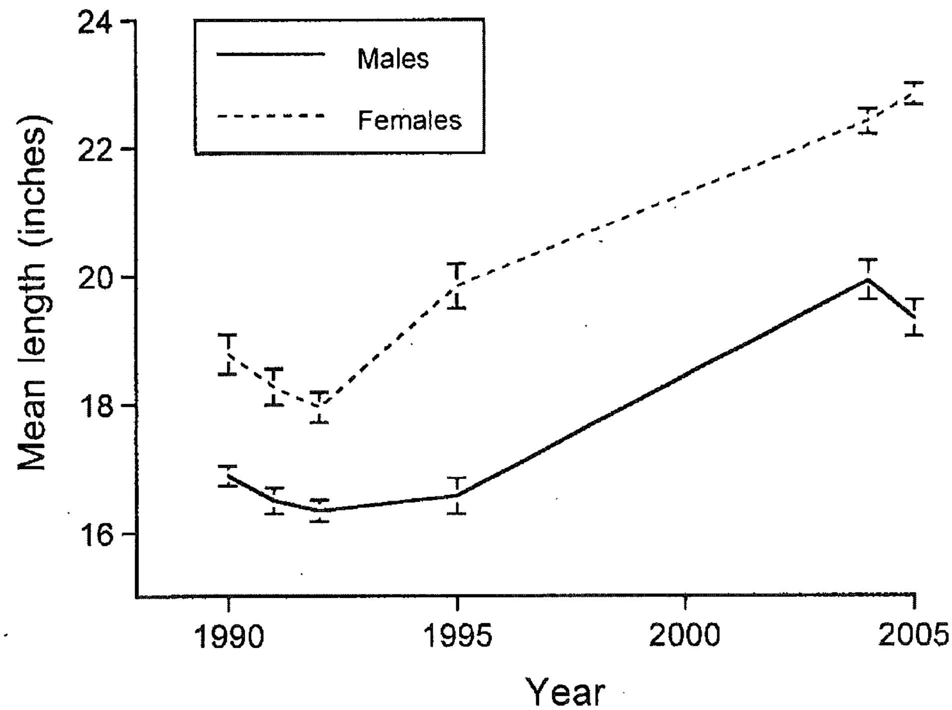

Figure 7. Mean lengths (± 1 SE) of northern pike caught by ice-out trapping in Coon-Sandwick Lake, 1990-2005.

References

Anderson, D. W., and D. H. Schupp. 1986. Fish community responses to northern pike stocking in Horseshoe Lake, Minnesota. Minnesota Department of Natural Resources, Section of Fisheries Investigational Report 387, St. Paul.

Bates, D., M. Maechler, and B. Dai. 2008. Lme4: linear mixed-effects models using S4 classes. R package version 0.999375-28. Available: http://lme4.r-forge.r-project.org/.

Bolker, B. M., M. E. Brooks, C. J. Clark, S. W. Geange, J. R. Poulsen, M. H. H. Stevens, and J. S. White. 2008. Generalized linear mixed models: a practical guide for ecology and evolution. Trends in Ecology and Evolution 24:127-135.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference a practical information-theoretic approach, second edition. Springer Science+Business Media, Inc. New York.

Burri, T. M. 2008. Angler creel survey of Pelican Lake, St. Louis County, May 12, 2007 through September 30, 2007. Minnesota Department of Natural Resources, Division of Fish and Wildlife Completion Report Job 786, F-29-R(P)-27. St. Paul.

Casselman, J. M. 1996. Age, growth and environmental requirements of pike. Pages 69-101 *in* J. F. Craig, editor. Pike biology and exploitation. Chapman and Hall, London.

Colby, P. J., P. A. Ryan, D. H. Schupp, and S. L. Serns. 1987. Interactions in north-temperate lake fish communities. Canadian Journal of Fisheries and Aquatic Sciences 44(Supplement 2):104-128.

Cook, M. F., and J. A. Younk. 1998. A historical examination of creel surveys from Minnesota's lakes and streams. Minnesota Department of Natural Resources, Section of Fisheries Investigational Report 464, St. Paul.

Craig, J. F. 2008. A short review of pike ecology. Hydrobiologia 601:5-16.

DuBois, R. B., T. L. Margenau, R. S. Stewart, P. K. Cunningham, and P. W. Rasmussen. 1994. Hooking mortality of northern pike angled through ice. North American Journal of Fisheries Management 14:769-775.

Erickson, M. L. 2005. Creel survey evaluation of experimental northern pike regulations on Lake Sallie and Lake Melissa, summer 2003 and winter 2003-2004, Becker County, Minnesota. Minnesota Department of Natural Resources, Division of Fish and Wildlife Completion Report Job 702, F-29-R-24. St. Paul.

Findlay, D. L., S. E. M. Kasian, L. L. Hendzel, G. W. Regehr, E. U. Schindler, and J. A. Shearer. 1994. Biomanipulation of Lake 221 in the Experimental Lakes Area (ELA): effects on phytoplankton and nutrients. Canadian Journal of Fisheries and Aquatic Sciences 51:2794-2807.

Fleiss, J. L., B. Levin, and M. C. Paik. 2003. Statistical methods for rates and proportions, third edition. John Wiley and Sons, Inc. Hoboken, New Jersey.

Gigliotti, L. M., and W. W. Taylor. 1990. The effect of illegal harvest on recreational fisheries. North American Journal of Fisheries Management 4:106-110.

Goeman, T. J., and P. J. Radomski. 1997. Statewide evaluation of experimental fishing regulations based on ecological lake classification. Minnesota Department of Natural Resources, Section of Fisheries Technical Report 1995-1997 to the Legislative Commission on Minnesota Resources, St. Paul.

Goeman, T. J., D. W. Anderson, and D. H. Schupp. 1990. Fish community responses to manipulation of yellow perch and walleye abundance. Minnesota Department of Natural Resources, Section of Fisheries Investigational Report 404, St. Paul.

Goeman, T. J., P. D. Spencer, and R. B. Pierce. 1993. Effectiveness of liberalized bag limits as management tools for altering northern pike population size structure. North American Journal of Fisheries Management 13:621-624.

Grimm, M. P. 1983. Regulation of biomasses of small (<41 cm) northern pike (*Esox lucius* L.), with special reference to the contribution of individuals stocked as fingerlings (4-6 cm). Fisheries Management 14:115-134.

Gurevitch, J., and L. V. Hedges. 1993. Meta-analysis: combining the results of independent experiments. Pages 378-420 *in* S. M. Scheiner and J. Gurevitch, editors. Design and analysis of ecological experiments. Chapman and Hall, New York.

Inskip, P. D., and J. J. Magnuson. 1986. Fluctuations in growth rate and condition of muskellunge and northern pike in Escanaba Lake, Wisconsin. American Fisheries Society Special Publication 15:176-188. Bethesda, Maryland.

Jacobson, P. C., and C. S. Anderson. 2007. Optimal stocking densities of walleye fingerlings in Minnesota lakes. North American Journal of Fisheries Management 27:650-658.

Kempinger, J. J., and R. F. Carline. 1978. Dynamics of the northern pike population and changes that occurred with a minimum size limit in Escanaba Lake, Wisconsin. American Fisheries Society Special Publication 11:382-389.

Kipling, C., and W. E. Frost. 1970. A study of the mortality, population numbers, year class strengths, production and food consumption of pike, *Esox lucius* L., in Windermere from 1944 to 1962. Journal of Animal Ecology 39:115-157.

Klefoth, T., A. Kobler, and R. Arlinghaus. 2008. The impact of catch-and-release angling on short-term behavior and habitat choice of northern pike (*Esox lucius* L.). Hydrobiologia 601:99-110.

Koski, K. 2006. Coon-Sandwick Lake creel survey report for the summer season of 2005. Minnesota Department of Natural Resources, Division of Fish and Wildlife Completion Report Job 722, F-29-R(P)-25. St. Paul.

Latta, W. C. 1972. To spear or not to spear the northern pike in Michigan: a simulation of regulations for fishing. Michigan Academician 5:153-170.

Margenau, T. L., S. P. AveLallemant, D. Giehtbrock, and S. T. Schram. 2008. Ecology and management of northern pike in Wisconsin. Hydrobiologia 601:111-123.

Moen, K. O. 2004. Summer and winter creel surveys of Julia, Medicine, and North Twin lakes, Beltrami County, Minnesota, 10 May 2003 – 15 February 2004. Minnesota Department of Natural Resources, Division of Fish and Wildlife Completion Report Job 703, F-29-R(P)-24. St. Paul.

Moyle, J. B. 1950. Gill nets for sampling fish populations in Minnesota waters. Transactions of the American Fisheries Society 79:195-204.

Moyle, J. B. 1956. Relationships between the chemistry of Minnesota surface waters and wildlife management. Journal of Wildlife Management 20:303-320.

Olson, D. E., and P. K. Cunningham. 1989. Sport-fisheries trends shown by an annual Minnesota fishing contest over a 58-year period. North American Journal of Fisheries Management 9:287-297.

Pierce, R. B., and M. F. Cook. 2000. Recreational darkhouse spearing for northern pike in Minnesota: Historical changes in effort and harvest and comparisons with angling. North American Journal of Fisheries Management 20:239-244.

Pierce, R. B., and C. M. Tomcko. 1997. Initial effects of slot length limits for northern pike in five north-central Minnesota lakes. Minnesota Department of Natural Resources, Division of Fish and Wildlife Investigational Report 454, St. Paul.

Pierce, R. B., and C. M. Tomcko. 1998. Angler noncompliance with slot length limits for northern pike in five small Minnesota lakes. North American Journal of Fisheries Management 18:720-724.

Pierce, R. B., and C. M. Tomcko. 2003a. Variation in gill-net and angling catchability with changing density of northern pike in a small Minnesota lake. Transactions of the American Fisheries Society 132:771-779.

Pierce, R. B., and C. M. Tomcko. 2003b. Interrelationships among production, density, growth, and mortality of northern pike in seven north-central Minnesota lakes. Transactions of the American Fisheries Society 132:143-153.

Pierce, R. B., C. M. Tomcko, and T. D. Kolander. 1994. Indirect and direct estimates of gill-net size selectivity for northern pike. North American Journal of Fisheries Management 14:170-177.

Pierce, R. B., C. M. Tomcko, and T. L. Margenau. 2003. Density dependence in growth and size structure of northern pike populations. North American Journal of Fisheries Management 23:331-339.

Pierce, R. B., C. M. Tomcko, and D. H. Schupp. 1995. Exploitation of northern pike in seven small north-central Minnesota lakes. North American Journal of Fisheries Management 15:601-609.

R Development Core Team. 2008. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available: www.R-project.org.

Schupp, H. H. 1992. An ecological classification of Minnesota lakes with associated fish communities. Minnesota Department of Natural Resources, Section of Fisheries Investigational Report 417, St. Paul.

Seaburg, K. G., and J. B. Moyle. 1964. Feeding habits, digestive rates, and growth of some Minnesota warmwater fishes. Transactions of the American Fisheries Society 93:269-285.

Sewell, D. 2006. Creel surveys of Sturgeon Lake (58-0067) and Island Lake (58-0062) during the 2005 open water angling season May 14, 2005 to October 15, 2005. Minnesota Department of Natural Resources, Division of Fish and Wildlife Completion Report Job 728, F-29-R(P)-25. St. Paul.

Shavlik, C. E. 2005. Ten Mile Lake creel survey May 14 to September 30, 2005. Minnesota Department of Fisheries and Wildlife, Division of Fish and Wildlife Completion Report Job 715, F-29-R(P)-25. St. Paul.

Snow, H. E., and T. D. Beard. 1972. A ten-year study of native northern pike in Bucks Lake, Wisconsin, including evaluation of an 18.0-inch size limit. Wisconsin Department of Natural Resources, Technical Bulletin 56. Madison.

Tomcko, C. M. 1997. A review of northern pike *Esox lucius* hooking mortality. Minnesota Department of Natural Resources, Division of Fish and Wildlife Fish Management Report 32, St. Paul.

Treasurer, J. W., R. Owen, and E. Bowers. 1992. The population dynamics of pike, *Esox lucius*, and perch, *Perca fluviatilis*, in a simple predator-prey system. Environmental Biology of Fishes 34:65-78.

Wesloh, M. L., and D. E. Olson. 1962. The growth and harvest of stocked yearling northern pike, *Esox lucius* Linnaeus, in a Minnesota walleye lake. Minnesota Department of Conservation, Division of Game and Fish Investigational Report 242, St. Paul.

Zar, J. H. 1984. Biostatistical analysis, second edition. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

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