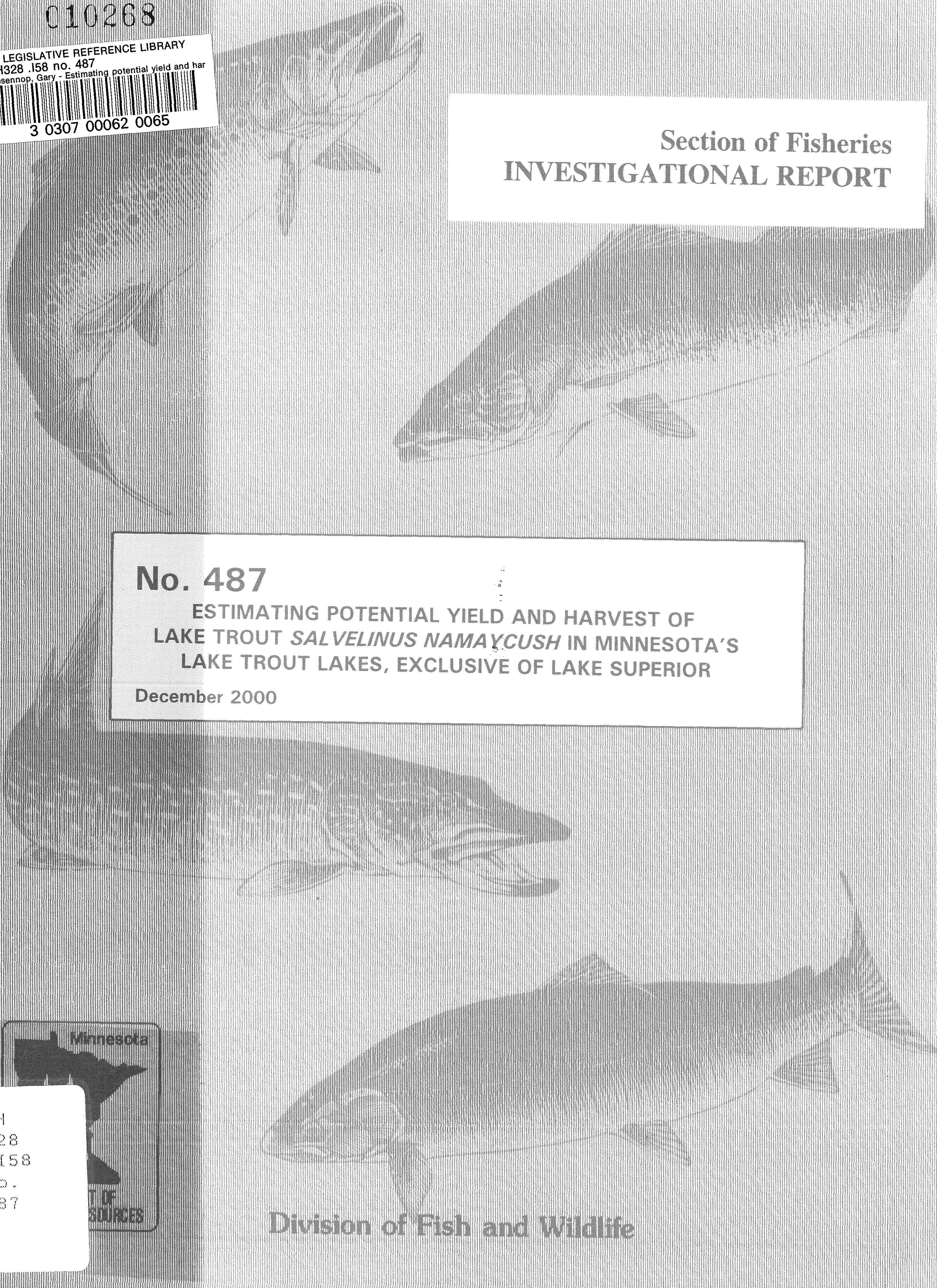

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No. 487

ESTIMATING POTENTIAL YIELD AND HARVEST OF LAKE TROUT *SALVELINUS NAMAYCUSH* IN MINNESOTA'S LAKE TROUT LAKES, EXCLUSIVE OF LAKE SUPERIOR

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Estimating Potential Yield and Harvest of Lake Trout *Salvelinus namaycush* in Minnesota's Lake Trout Lakes, exclusive of Lake Superior[1].

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Abstract.-- Estimates of optimal thermal habitat volume (THV) for lake trout indicate that about 12 percent of the total lake volume of the average Minnesota lake trout lake has temperature and dissolved oxygen conditions considered optimal for lake trout growth and long-term survival in July and early August. Lakes for which optimal thermal habitat was limited by reduced oxygen concentrations (<6.0 mg/l) had an average mean depth of 7.6 m (N=21) while lakes for which optimum thermal habitat was not limited by oxygen had an average mean depth of 12.1 m (N=79). The volume of optimum lake trout habitat may be more oxygen-limited in August and September than in July, particularly in relatively small lakes. Oxygen depletion in the hypolimnion and metalimnion during mid-to-late summer is a result of natural lake processes in remote lakes, but the rate and extent of oxygen depletion may be increased by habitat degradation in more accessible and developed lakes.

Potential lake trout yield based on JulyTHV averaged 1.51 $kg \cdot ha^{-1} \cdot year^{-1}$ and ranged from zero to 3.77. The range of these yield estimates was broader than the range of lake trout yields (0.37 to 1.01 $kg \cdot ha^{-1} \cdot year^{-1}$) derived from the morphoedaphic index (MEI). With few exceptions, lake trout yield and harvest data for most of Minnesota's lake trout sport fisheries is undocumented or greater than 15 years old, and is limited to the winter angling season, especially for remote lakes. Existing creel data indicates that some lake trout lakes may have been over fished in the past. There is, however, a continuing need to determine the use and status of Minnesota's lake trout populations because there is a continuing interest in lake trout angling in relatively remote and more accessible lakes. Criteria for estimating lake trout thermal habitat quantity and quality need revision to account for differences in lake trout behavior with respect to temperature and forage, especially in small lakes with simple fish communities. Until lake trout community dynamics are better documented or sustainable lake trout yields are determined empirically, the MEI and THV potential yield estimates are recommended as guidelines for evaluating observed lake trout yields and harvest levels.

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[1] This project was funded in part by the Federal Aid in Sport Fish Restoration (Dingell-Johnson) Program. Completion Report, Study 655, D-Project F-26-R Minnesota.

Introduction

Lake trout *Salvelinus namaycush* are particularly vulnerable to overexploitation because they are characterized by slow growth, late sexual maturity, low reproductive potential, and a slow replacement rate (Shuter et al. 1998). Naturally reproducing lake trout populations with annual yields more than 0.45 kg·ha^{-1}·year^{-1} (0.4 lb·acre^{-1}·year^{-1}) are likely over fished (Healy 1978). Martin and Olver (1980) suggested lake trout yields should fall in the range of 0.25 - 0.75 kg·ha^{-1}·year^{-1} for self-sustaining populations. Macins (1985) found signs of overfishing in Whitefish Bay of Lake of the Woods where annual yields were 0.22 to 0.34 kg·ha^{-1} ·year^{-1}. In southern Ontario, the quality of many lake trout fisheries is declining because fishing effort (angler-hours per hectare) is often high and annual harvest often exceeds annual production (Evans et al. 1991). According to Shuter et al. (1998) lake trout fisheries in northern Ontario were expected to show declining trends if angling effort and mortality due to fishing were not constrained within sustainable limits. It would not be surprising if some of Minnesota's unstocked lake trout lakes are overstressed and in decline or at risk.

Ryder (1965) suggested that the morphoedaphic index (MEI: i.e., total dissolved solids/mean depth) could be used to estimate potential productivity of northern temperate lakes. The Ontario Ministry of Natural Resources (1982) used the MEI empirical yield formula of Ryder et al. (1974) to estimate potential fish yield for many Ontario lakes, and showed how it could be partitioned by species. For lake trout, they suggested an allowable or safe yield guideline to be 25 percent of the total potential MEI yield for both sport and commercial fisheries. Payne et al. (1990), apparently dissatisfied with the variability of MEI data, expanded on the thermal habitat work of Christie and Regier (1988), and recommended that potential lake trout harvest (kg/year) could be calculated from their formula relating empirically observed sustained harvest to July thermal habitat volume (THV). More recently, Ryan and Marshall (1994) predicted lake habitat based on mean depth and primary productivity, and then developed a niche definition for lake trout based lake trout presence or absence and oxygen depletion during late summer. They showed how lake trout populations that may be at risk to natural or human induced stress may be identified. Marshall (1996) developed and explained a hierarchical method of assessing habitat suitability and yield potential of lake trout lakes. Most recently, Shuter et al. (1998) developed a model for managing inland lake trout stocks in Ontario.

Lake trout are indigenous to many northeastern Minnesota lakes and may be vulnerable to over- harvest. At certain times of the year, lake trout can be relatively easy to catch. Lake trout are sought by many Minnesota and nonresident anglers, although they are not as widely distributed, abundant or popular as walleye *Stizostedion vitreum*, northern pike *Esox lucius*, and various centrarchids (bluegill, black bass, and crappie). In Minnesota, small to large groups of anglers make annual trips to selected lakes when the lake trout angling season opens in mid-May, usually shortly after ice-out and before thermal stratification. During this period, lake trout can often be found in relatively shallow water and may readily strike various lures or baits. In summer, when occupying deep, relatively cold water, lake trout may be taken by jigging or deep trolling. In late September, prior to spawning in early to mid-October, when the season is closed, they may again be sought in relatively shallow water. In winter, angling for lake trout through the ice is a popular activity. At times, lake trout can be readily caught by anglers using jigging rods, tip-ups, or hand-lines with artificial lures or hooks baited with live or dead bait.

Reliable angling effort, harvest, yield, and population dynamics information for Minnesota's self-sustaining lake trout populations are rare at best. Although many people fish for lake trout, harvest and yield data are sparse or nonexistent, especially for lakes accessible only by portages. Angler use of the lake trout resource in the Boundary Waters Canoe Area Wilderness (BWCAW) is poorly documented. For the most part, lake trout harvest information is limited to the winter season and is relatively old (*circa*, 1980). In some cases, the creel survey data were gathered during exit interviews at BWCAW entry locations, not on the lakes fished, thus harvest data may be biased (D. Thompson, personal communication 1999). Also, most BWCAW lakes are no longer legally accessible by snowmobile in the winter. Thus, historical use and harvest information has uncertain relevance to current resource use. Recent creel information (*circa*, 1990s) applies to lakes outside the BWCAW or on its periphery. Therefore, the most recent and most reliable creel data do not directly apply to the unstocked lake trout fisheries that are mostly within in the BWCAW.

Lake trout population estimates exist only for Gillis Lake in the BWCAW interior (MNDNR files). The estimates for Gillis Lake (240 ha) ranged from 2.7 to 6.2 adults/ha (641 to 1,443 adults), but were based on few recaptures (2 to 6 fish). For comparison, population density estimates ranged from 3.2 to 31.9 adults/ha for several Alaskan lakes (Burr 1991). For a 67 ha lake in Ontario, McAughey and Gunn (1995) reported 5.5 to 6.2 adults/ha. In Minnesota, lake trout gill net relative abundance (catch-per-unit-effort = CPUE) data often is sketchy because sampling efforts are infrequent (often less than once per decade), and CPUE often is based on few gill net lifts (usually less than 6), particularly on small lakes whose lake trout populations may potentially be damaged by intensive sampling.

To date, funding constraints, logistics of sampling remote lakes, and wilderness regulations or policies have made it virtually impossible to gain detailed angler use and populations dynamics information from more than a handful of lake trout lakes. Yet, estimates of potential fish yield and specifically lake trout yield for Minnesota's lakes are needed to deal with potential resource allocation issues. The major objectives of this project are: 1) to evaluate and characterize all of Minnesota's lake trout lakes by depth-temperature and dissolved oxygen profiles; 2) to estimate optimal thermal habitat volume for lake trout in summer; 3) to calculate initial estimates of potential lake trout yield based on THV and MEI; and 4) where possible, to relate these to existing lake trout harvest estimates.

Study Sites

Most of Minnesota's lake trout lakes (110+) are in the northern part of Cook and Lake counties, the two most northeasterly counties, and lie within 30 km of the Minnesota-Ontario border (Figure 1). Most are within the boundaries of the Superior National Forest and many of these are within the BWCAW. Three lake trout lakes are within Voyageurs National Park, and another three are in the Chippewa National Forest. Several lakes to the south and west of their native range have managed lake trout populations, and some of these lakes have shown potential for long term lake trout survival. The majority of lakes containing lake trout are found in the Canadian provinces (Scott and Crossman 1973). Lake trout are present in about 2,200 Ontario lakes (Shuter et al. 1998), and some of Minnesota's largest lake trout lakes straddle the Minnesota-Ontario border. Jurisdiction and management of these border waters are shared with Ontario provincial agencies.

Most of Minnesota's lake trout lakes outside the BWCAW have been stocked in the past, and some continue to receive maintenance stocking, while most unstocked lake trout lakes are in the BWCAW. Current lake trout management in the BWCAW relies on the assumption that natural reproduction is sufficient and angler harvest low enough to allow these populations to sustain themselves. Some heavily fished lakes outside the BWCAW borders are stocked to maintain populations. In recent years, however, lake trout stocking has been curtailed on several lakes to see if natural reproduction will sustain viable sport fisheries (S. Persons, personal communication 1999). Also, native Minnesota strain lake trout from Gillis Lake have been introduced into a few lakes, apparently barren of lake trout, to see if they will become established and maintain a viable fishery without further stocking.

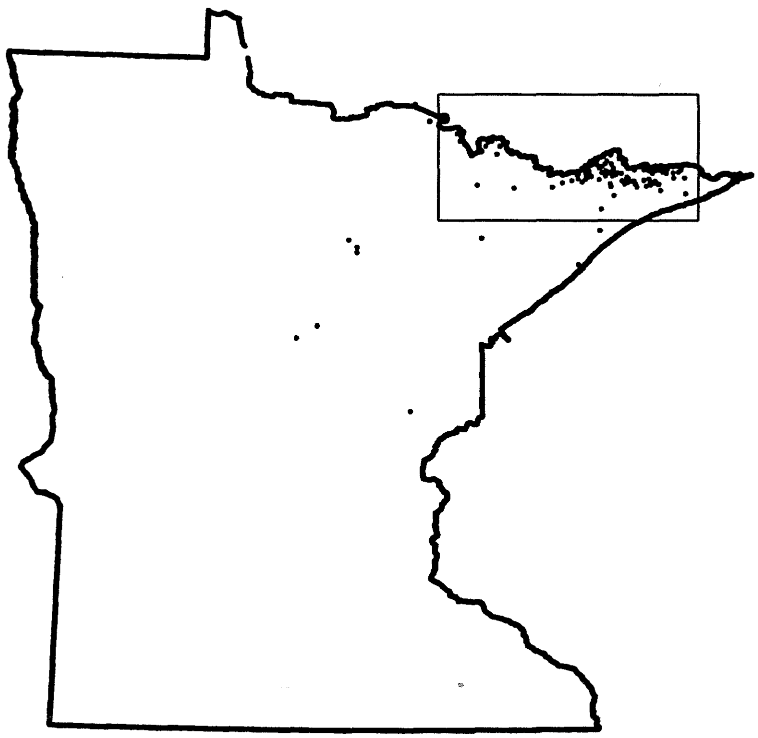

Figure 1. Approximate location of Minnesota's lake trout lakes. Over 90 percent of the lakes are encompassed by the rectangle.

Minnesota lakes known to have lake trout populations (Table 1) range from 11 to 7,120 ha ($\bar{x}$ = 350 ha). Maximum depths range from 8 to 85 m ($\bar{x}$ = 31 m), while mean depths range from 3.8 to 27.0 m ($\bar{x}$ = 11.1 m). Estimated total lake volume ranges from 0.9 to 459 cubic hectometers ($\bar{x}$ = 43.7 hm^3). [One cubic hectometer (i.e., 1 hm^3 = 100m·100m·100m = 1,000,000 m^3) is approximately equivalent to 811 acre-feet.] Also, many of Minnesota's lake trout lakes are small. Approximately 49% are <100 ha, while 34% are between 100 and 500 ha, and only 17% are >500 ha. Many northeastern Minnesota lake trout lakes are relatively infertile and have a relatively low buffer capacity, as indicated by total alkalinity ($\bar{x}$ = 19 mg/l, as $CaCO_3$). Total dissolved solids (TDS), an indicator of potential fish yield, ranged from 11.3 to 164 mg/l ($\bar{x}$ = 37; median = 25). Approximately 60% of the lakes have TDS values less than 30 mg/l. Secchi disc visibility estimates in these lakes ranged from 1.4 to 9.3 meters ($\bar{x}$ = 4.8 m; median=4.6 m).

The classic lake trout lake is deep, cold, oligotrophic, relatively low in nutrients, and is well-oxygenated in deep water throughout the year. Despite this generalization, lake trout are found in many lakes that show some degree of oxygen depletion in the hypolimion or metalimnion during the summer. Ryan and Marshall (1994), citing Charlton (1980) and Cornett and Rigler (1980), note that lake trout habitat volume during the stratified period depends on the initial oxygen supply at spring mixing, the rate of oxygen depletion during the stratified period, and the time between lake overturns. The classic lake trout lake typically has an orthograde oxygen curve during summer stratification, with relatively high oxygen concentrations (e.g., 8 mg/l) from the surface to nearly the lake bottom, sometimes with a metalimnetic oxygen maximum in the thermocline. A clinograde oxygen curve, typical of more eutrophic lakes, shows a sharp decline in oxygen concentrations in the thermocline, with oxygen generally continuing to decline with increasing depth, often paralleling decreasing temperature. Among Minnesota's lake trout lakes, there are many intermediate variations between these two extreme types.

Methods

Temperature-oxygen-depth profiles (*N*>1,000) measured from June through September 1939-1999 were collected from paper and electronic data files from various sources, including MNDNR, Minnesota Pollution Control Agency, and Voyageurs National Park. Temperature (°C) and dissolved oxygen (mg/l) data were plotted versus depth (m) to better evaluate the data and to characterize the study lakes. Additional chemical data (total alkalinity, conductivity, and total dissolved solids), and physical data (Secchi disk visibility) were gathered from these agencies. Additional measurements were made in summers of 1997-1999 to better characterize and compare the lakes. Water temperature and dissolved oxygen were measured (usually with a Model 57 Yellow Springs Instrument[2] meter, equipped with a 61 m cable and stirring device) from lake surface to bottom, usually at the deepest known site. Measurements were generally at 1.0 m or at 0.5 m intervals, with greater detail obtained in the metalimnion or where temperature or oxygen concentration changed rapidly. In 1998, conductivity and TDS were measured with a Markson portable meter (model CNTDS72), while in 1999 these measurements were made with an Oakton portable meter (model WB-35607-20). Total alkalinity was determined by double end point potentiometric titration of surface water samples brought to the laboratory.

Available historical and newer depth-temperature-oxygen data were entered directly from paper files to SYSTAT (Wilkinson 1997) data files, while other data previously recorded in other electronic formats (DBASE, LOTUS, and STORET) were also imported into SYSTAT. I examined graphs of temperature and oxygen plotted against depth, noting depth and dissolved oxygen concentrations at 12° and 8°C. Then, although there was a broad range of

[2] Use of product names does not imply endorsement.

Table 1. Morphometric and selected chemical parameters of Minnesota lakes known to have a lake trout population. Total alkalinity is expressed, as mg/l $CaCO_3$, and was measured by potentiometric titration. Asterisks denote lakes for which total dissolved solids (TDS) was estimated (inferred) from TDS measurements of other lakes in the same general location. Lakes are listed by county and by lake area in decreasing order.

Lake name	MN lake number	Surface area (ha)	Depth max. (m)	Depth mean (m)	Depth median (m)	Total volume (hm^3)	Total alkalinity (mg/l)	Conductivity (μs)	TDS (mg/l)	Secchi disc visibility (m)
Roosevelt	11-0043	600	39.3	14.8	12.9	88.9	128	-	144	5.2
Brule	16-0348	1,884	23.8	8.6	8.4	161.7	6.5	35.6	20.3	5.1
Seagull	16-0629	1,609	44.2	11.1	9.6	178.0	13.4	40.3	25*	4.0
Gunflint	16-0356	1,570	61.0	27.1	22.3	423.6	19.9	54.5	43.8	4.5
North	16-0331	1,117	38.1	15.0	14.6	167.2	41.5	95.5	79.0	8.2
Pine	16-0041	917	34.4	16.8	16.4	153.8	15.3	40.3	25*	6.8
Mountain	16-0093	836	64.0	17.6	13.7	147.1	11.8	45.0	25*	8.3
Greenwood	16-0077	818	30.8	9.9	8.8	80.8	5.7	28.9	16.3	4.6
Saganaga, Little	16-0809	644	45.7	8.6	5.5	55.2	9.5	35.4	22.1	3.0
Clearwater	16-0139	523	39.9	15.1	13.1	79.1	12.8	41.9	25*	7.4
Gabimichigami	16-0811	495	63.7	22.2	19.4	109.8	10.2	34.3	18.4*	4.2
South	16-0244	485	43.0	19.2	17.8	93.1	21.4	64.8	35*	9.2
Rose	16-0230	482	29.3	11.4	9.4	54.9	16.0	-	35*	5.9
Loon	16-0448	436	65.5	21.6	17.5	94.3	12.5	45.0	28.1	4.6
Alton	16-0622	421	22.0	7.3	6.3	30.0	9.9	33.1	20*	4.8
Moose	16-0043	410	34.4	15.7	14.1	64.5	10.0	-	25*	5.1
Alpine	16-0759	341	19.8	5.7	5.0	19.5	13.2	41.5	23.9*	4.5
Long Island	16-0460	339	25.9	8.1	7.4	27.6	6.9	31.9	18.9	2.5
Tuscarora	16-0623	333	39.6	10.9	9.9	36.5	11.0	46.0	23.1	4.3
Winchell	16-0354	332	40.2	11.6	9.9	38.6	6.9	36.9	20*	5.2
Cherokee	16-1524	308	43.3	10.5	8.2	32.3	5.4	27.9	23.0	3.4
Poplar	16-0239	308	22.3	7.0	5.9	21.4	8.5	34.0	52*	3.4
Pike, West	16-0086	285	36.9	10.0	8.3	28.6	13.3	43.4	25*	6.3
Saganaga	16-0633	7,120	85.3	(map of Red Rock Bay only)			--	-	-	
Red Rock Bay	16-0633	280	26.5	5.8	4.9	16.2	15.5	51.1	25*	4.5
Gillis	16-0753	240	56.4	19.1	16.5	45.8	11.2	37.6	23.0	5.1
Bearskin, East	16-0146	236	20.4	6.8	5.1	15.9	8.3	-	25*	3.6
Alder	16-0114	215	22.0	9.1	8.7	19.7	10.2	38.4	25*	4.9
Bearskin, West	16-0228	200	23.8	10.2	9.5	20.4	17.8	62.5	44.9	5.8
Duncan	16-0232	195	35.4	14.3	11.8	27.9	16.8	51.3	35*	5.4
Daniels	16-0150	186	27.4	10.8	10.5	20.0	13.1	43.1	23.5	5.7
Magnetic	16-0463	176	27.4	12.2	11.5	21.4	17.0	-	25*	5.2
Maraboeuf	16-0610	161	16.8	(no depth map available)			18.9	54.3	25*	3.7
Red Rock	16-0793	152	19.5	7.1	6.3	10.7	2.3	59.6	25*	3.9
Davis	16-0435	147	19.5	8.6	9.1	12.7	2.5	20.7	11.3	3.7
Flour	16-0147	134	22.9	8.6	7.7	11.5	17.3	51.2	25*	5.9
Trout	16-0049	104	23.5	10.5	10.1	10.9	12.6	39.3	20*	5.9
Peter	16-0757	102	36.6	13.4	12.4	13.7	14.8	34.9	18.4*	5.5
Moss	16-0234	100	29.0	13.1	11.7	13.1	17.8	51.5	28.6	4.2
Birch	16-0247	100	21.0	7.9	7.1	7.9	15.7	57.4	42.1	5.4
Jasper	16-0768	98	38.1	10.6	8.2	10.5	12.6	41.9	25*	3.8
Gneiss	16-0617	97	20.0	8.1	8.1	7.5	22.6	51.4	25*	3.2
Wine	16-0686	96	19.8	3.8	2.9	3.6	4.1	18.0	15*	3.7
Frost	16-0571	96	26.8	10.7	11.1	10.2	9.7	37.0	22.5	3.7
Vernon	16-0267	95	30.8	10.8	8.1	10.2	8.2	35.4	20.8	4.3
Crooked	16-0723	94	22.9	8.0	7.2	7.6	11.5	48.4	24.2	2.9
Mayhew	16-0337	90	25.6	11.2	10.3	10.1	15.0	46.5	35.8	6.7
Crystal	16-0090	85	27.7	12.1	11.4	10.3	10.4	33.2	20*	4.9
Swan	16-0268	74	37.2	13.6	10.2	10.1	9.5	44.8	22.6	3.4
Kemo	16-0188	74	19.8	11.0	11.7	8.2	11.0	-	25*	5.6
Mesaba	16-0673	74	19.8	7.4	7.1	5.5	4.3	-	15*	3.4
Howard	16-0789	62	38.1	14.7	13.9	9.0	12.1	43.9	21.9*	3.4

Table 1. Continued.

Lake name	MN lake number	Surface area (ha)	Depth max. (m)	Depth mean (m)	Depth median (m)	Total volume (hm³)	Total alkalinity (mg/l)	Conductivity (µs)	TDS (mg/l)	Secchi disc visibility (m)
Trout, Little	16-0170	49	17.1	7.3	6.6	3.6	13.8	45.1	26.8	3.8
Gordon	16-0569	49	29.0	7.5	6.4	3.7	5.8	35.3	17.6	3.7
Jap	16-0626	48	21.3	9.3	9.0	4.5	10.7	39.9	20*	3.1
Snipe	16-0527	48	27.4	4.3	2.7	2.0	7.5	44.0	25.7	1.4
French	16-0755	45	39.6	17.9	16.3	8.0	9.0	40.5	22.0	3.1
Karl	16-0461	44	22.9	4.8	1.2	2.1	6.8	38.3	19.2	2.7
Partridge	16-0233	43	25.0	10.7	10.6	4.7	17.6	55.6	35*	2.7
Dunn	16-0245	36	20.1	7.5	5.8	2.7	23.3	-	35*	4.1
Owl	16-0726	33	21.3	6.8	5.9	2.2	9.9	43.1	21.6	4.9
Town	16-0458	32	22.0	9.3	9.0	3.0	5.3	33.1	16.6	3.4
Bat	16-0752	32	33.5	13.4	11.6	4.3	9.5	33.1	19.7	4.6
Fern, West	16-0718	30	21.3	9.8	10.2	3.0	10.9	42.7	21.4	5.4
Cash	16-0438	30	17.7	6.2	5.6	1.9	4.4	-	20*	1.9
Ram	16-0174	27	12.2	6.0	6.0	1.6	14.0	40.7	24.1	5.5
Fay	16-0783	26	19.8	9.9	9.5	2.6	8.0	40.1	21.6	4.2
Jim	16-0135	24	7.9	4.7	5.0	1.1	7.8	-	15*	3.0
Misquah	16-0225	23	18.6	9.5	9.5	2.2	11.6	54.8	27.7	2.4
Virgin	16-0719	23	12.2	6.1	5.8	1.4	12.1	40.8	20.5	3.4
Fern	16-0716	23	21.3	10.0	9.9	2.3	9.3	45.0	22.0	3.5
State	16-0293	21	15.2	5.9	4.6	1.3	-	-	-	-
Powell	16-0756	21	22.9	8.0	6.2	1.7	9.6	39.9	19.9	4.5
Blue Snow	16-0532	20	15.2	(no depth map available)			8.7	-	14.4	4.3
Big Trout	18-0315	543	39.0	15.6	15.3	84.8	113.0	-	164.0	6.2
Trout, Little	31-0394	29	24.4	11.7	11.2	3.5	153.9	195.0	130*	6.2
Bluewater	31-0395	147	36.6	15.1	14.9	22.2	99.2	225.0	148.0	5.6
Trout	31-0410	709	47.9	13.8	12.3	97.6	126.0	186.7	132.0	3.7
Caribou	31-0620	97	46.3	14.6	14.2	14.1	17.0	38.3	38.0	9.3
Knife: all	38-0404	2,114	54.6	(see below)		336.9	-	-	48*	-
South Arm	38-0404	864	39.6	14.5	14.0	125.2	27.0	69.0	48.0	7.4
North Arm	38-0404	658	54.6	20.1	17.8	132.2	-	-	-	-
West Arm	38-0404	592	39.6	13.4	12.8	79.5	-	-	-	-
Snowbank	38-0529	1,335	45.7	14.8	12.3	197.8	12.5	40.1	18.7	5.9
Kekekabic	38-0226	675	59.4	22.8	21.1	153.7	13.3	42.6	18.9*	5.9
Thomas	38-0351	602	33.5	8.4	7.1	50.6	8.5	32.2	19.8	4.1
Cypress(Ottertrack)	38-0211	468	35.4	10.9	10.4	51.0	36.5	86.8	68.0	7.1
Ima (Slate)	38-0400	308	35.4	11.9	9.3	36.5	9.4	34.6	20.3	3.6
Ogishkemuncie	38-0180	284	22.9	7.5	6.1	21.4	9.6	34.3	15.4*	4.5
Knife, Little	38-0229	259	56.1	21.7	21.5	56.2	32.4	-	64.0	6.5
Fraser	38-0372	257	31.7	8.9	8.0	22.8	8.6	33.3	19.6	4.6
Ester	38-0207	169	33.5	10.6	10.1	17.8	27.3	59.5	35.7	6.0
Amoeber	38-0227	157	33.5	11.3	9.5	17.7	19.1	52.1	25*	5.9
Ojibway	38-0640	123	35.1	9.2	6.2	11.3	34.0	74.0	40*	4.9
Hanson	38-0206	114	30.5	12.7	12.3	14.4	33.7	59.5	40.5	4.8
Raven	38-0113	83	17.1	7.4	7.4	6.1	12.2	30.7	25*	6.5
Cherry	38-0166	59	30.2	12.6	12.1	7.4	25.3	53.0	25*	6.8
Makwa	38-0147	58	23.2	9.2	7.9	5.3	14.3	45.5	22.8	5.1
Topaz	38-0172	54	21.3	5.7	4.5	3.1	25.7	-	25*	3.6
Gijikiki	38-0209	45	25.0	8.8	8.6	4.0	27.1	50.6	34.9	6.5
Holt	38-0178	44	22.3	8.1	7.8	3.6	25.5	40.3	19.9*	5.4
Missionary	38-0398	44	21.6	10.8	13.1	4.7	27.0	59.4	29.3	5.9
Strup	38-0360	42	32.0	8.9	5.6	3.8	6.4	28.8	25*	2.5
Rabbit	38-0214	42	32.0	12.9	13.3	5.4	21.4	51.1	31.4	4.8
Wisini	38-0361	38	41.8	13.1	11.6	5.0	7.0	27.2	25*	3.1

Table 1. Continued.

Lake name	MN lake number	Surface area (ha)	Depth max. (m)	Depth mean (m)	median (m)	Total volume (hm³)	Total alkalinity (mg/l)	Conductivity (µs)	TDS (mg/l)	Secchi disc visibility (m)
Sema (Coon)	38-0386	33	22.0	10.1	10.4	3.3	29.5	65.3	25*	4.2
Ahsub	38-0516	24	23.8	8.7	7.8	2.1	14.5	41.5	27.1	6.0
Explorer	38-0399	24	22.9	10.2	10.7	2.4	19.0	42.9	28.2	7.0
Kek	38-0228	23	42.1	18.0	16.2	4.2	22.8	58.0	28.9*	5.1
Lunar (Moon)	38-0168	23	18.9	6.7	5.7	1.6	14.6	46.3	25*	4.5
Ahmakose	38-0365	15	22.9	8.3	7.8	1.3	9.0	28.6	19.0	5.6
L. of the Clouds	38-0169	12	33.5	7.7	2.7	0.9	12.1	38.9	25*	4.3
Grindstone	58-0123	213	46.6	22.7	23.5	48.5	48.0	-	86.0	4.7
Lac La Croix	69-0224	5,967	39.9	7.7	5.1	458.7	13.0	42.0	25*	4.0
Trout, Big	69-0498	3,294	29.9	12.5	11.4	411.4	7.5	30.0	32.0	4.6
Burntside	69-0118	2,874	38.4	12.2	11.3	351.1	7.6	31.1	33.9	6.8
Mukooda	69-0684	308	23.8	12.2	13.5	37.6	24.7	58.3	38.0	3.2
Oyster	69-0330	292	39.6	13.3	11.6	38.8	6.3	29.4	17.0	3.4
Takucmich	69-0369	131	45.7	13.5	9.8	17.6	5.5	26.0	15.0	5.6
Trout, Little	69-0682	97	29.0	13.1	12.0	12.7	29.1	39.4	22.0	5.9
Gun	69-0487	72	41.8	10.9	9.1	7.8	3.7	22.5	15*	7.7
Cruiser	69-0832	46	27.7	13.2	13.4	6.2	6.1	21.7	17.0	8.3
Fat	69-0481	41	15.2	6.6	5.4	2.8	4.7	20.5	15*	5.2
Summary statistics:										
mean		346.7	30.6	10.9		43.4	18.7	47.4	36.7	4.8
minimum		11.5	7.9	3.8		0.9	2.3	18	11.3	1.4
maximum		7,119.9	85.3	27.0		459.0	128	225	164	9.3
N		122	122	122		122	122	104	69	122

depth-temperature-oxygen curve forms among lakes, I roughly categorized each lake as having a clinograde, orthograde, or intermediate form oxygen-depth curve based on the general relationship of the oxygen to the July and early August temperature-depth curves. I further categorized lakes by the presence or absence of increases or decreases in metalimnetic oxygen (Reid 1961).

Morphometric lake maps were digitized. Lake area (acres) at various depths (ft), and maximum, mean, and median depths originally were entered on LOTUS spreadsheets. Then, lake volumes (acre-ft) of various depth strata were estimated: $V = 0.5(A_1+A_2)(D_2-D_1)$, where: D = depth, A = area, and V=volume. These data were imported into SYSTAT files and converted to equivalent metric units.

The methods of Payne et al.(1990) were adapted to estimate the volume of optimal thermal habitat for lake trout for each lake included in this study. Those investigators defined July thermal habitat volume (JulyTHV) as the volume of water bounded by 12° and 8°C, and having a minimum of 6 mg/l dissolved oxygen. I categorized the lakes based on whether summer lake trout habitat was limited by dissolved oxygen. Evans et al. (1991) estimated that the average oxygen concentration at which lake trout swimming activity increases in response to declining oxygen (i.e., the median upper oxygen response threshold for adult lake trout) was 5.8 ±0.5 mg/l. They estimated the average oxygen concentration at which lake trout show an avoidance response (i.e., the median lower oxygen response threshold) was 4.2 ±0.6 mg/l). MacLean et al. (1990) suggested 6.0 mg/l as the lower oxygen threshold for optimal lake trout habitat. Thus, for lakes having some amount of oxygen depletion within the 12° to 8°C stratum (i.e., $O_2 < 6.0$ mg/l) the depth(s) at which this occurs becomes the lower bound (occasionally the upper bound) of the stratum used to calculate optimal thermal habitat. For each lake, I calculated THV_6 ($O_2 \geq 6$ mg/l) for all available depth-temperature-oxygen (DTO_2) profiles for dates from June through early September, so temporal changes could be observed for a few lakes having multiple DTO_2 profiles within and among years. For some DTO_2 profiles, where July THV_6 was zero (i.e., dissolved oxygen being less than 6.0 mg/l in the entire 12° to 8°C stratum), I also calculated THV_5 and THV_4, relaxing the oxygen constraint to 5.0 mg/l and then to 4.0 mg/l, respectively. I used 4.0 mg/l as a lower bound for estimating marginally suitable habitat volume for some lakes with significant oxygen depletion. For lakes having more than one estimate of $JulyTHV_6$, I calculated the mean of the $JulyTHV_6$ estimates. For each DTO_2 profile for each lake, I also calculated relative THV_6 (i.e., the proportion of the total lake volume having optimal thermal conditions for lake trout) [Relative THV = JulyTHV / total lake volume]. For each Minnesota lake trout lake that had been mapped and digitized and for which I had at least one estimate of $JulyTHV_6$ (N=118), I then estimated sustainable lake trout harvest by applying the empirical relationship to thermal habitat volume suggested by Payne et al. (1990):

$$\log_{10}(\text{Harvest}) = 2.15 + 0.714 \log_{10}(\text{JulyTHV}), \quad R^2=0.967.$$

Finally, an estimate of potential lake trout yield was obtained by dividing this harvest estimate by lake area.

Throughout this study, I use the terms harvest and yield as used by Payne et al. (1990). Total harvest is the total quantity of fish removed by anglers from an ecosystem or fish community per unit time, usually on an annual basis (e.g., kg/year, or kg/season). Yield is the amount of fish harvested (i.e., removed by anglers) expressed per unit surface area and per unit time (e.g., $kg \cdot ha^{-1} \cdot year^{-1}$).

Payne et al. (1990), however, made several cautions regarding the use of the JulyTHV method. THV lake trout yield estimates are imprecise, have wide confidence intervals, and using them to make harvest decisions for individual lakes involves risks. Thus, a given THV yield level is a guideline for management and may not insure sustainable harvest for a specific lake trout population. These authors also caution that for small lakes (<100 ha) actual lake trout yields may be higher than the estimate because they may have low species diversity and dense populations of planktivorous or benthivorous lake trout with few competing predators (Carl et al. 1990). Also, yield estimates derived from multiple years of DTO_2 data are preferable to those from a single year's data.

For 118 lakes, potential THV lake trout yield was compared to potential MEI yield of major fish species. For 69 of the 118 lakes, for which TDS had been measured and mean depth was known, I calculated the morphoedaphic index (MEI = TDS/mean depth; Ryder 1965). For the remaining 49 lakes for which TDS had not been measured, I calculated an estimate of MEI. In these cases, I used an estimated TDS value by assigning a TDS value from another lake in the general vicinity, or where lakes with known TDS values where clustered I assigned a local mean TDS to a nearby lake with an unknown TDS value. Potential yield of major fish species was calculated as: $Y = 1.4(\text{MEI})^{0.45}$, where Y=yield ($kg \cdot ha^{-1} \cdot year^{-1}$). Ontario fisheries biologists suggested that a sustainable lake trout yield may be 25% of the potential MEI yield for medium and large Ontario lakes (Ontario Ministry of Natural Resources 1982). At that time, this was their guideline for a safe or allowable lake trout yield that theoretically would allow maintenance of fish community structure, including lake trout brood stock maintenance and stock rehabilitation. Therefore, I selected 25% of the total potential MEI yield, as a reference to compare MEI lake trout yield to the July THV_6 lake trout yield.

To compare MEI and THV_6 lake trout harvest and yield estimates to empirical data, I obtained harvest and yield estimates derived from winter and summer angler creel surveys (Cook and Younk 1998; Eiler 1993; Heywood 1981; Persons 1984-1997; Persons and Hirsch 1989; Siesennop 1992) (Appendix Table 1).

Results

The majority of Minnesota's lakes where lake trout are known or believed to be present do not have high concentrations of dissolved oxygen from surface to bottom during the entire summer and early fall (Table 2). Only 17% (*N*=23) of the lakes examined had orthograde oxygen-depth curves in July and early August, while nearly 72% (*N*=96) were of the clinograde type, oxygen declining from the metalimnion (thermocline) to lake bottom. Eleven % (*N*=15) were intermediate between orthograde and clinograde.

Nearly 54 percent of the lakes showed increases in dissolved oxygen (1-2 mg/l) in the thermocline (metalimnetic maxima), often followed by a steady decline in oxygen at greater depths. In 10% of the lakes, dissolved oxygen increased only slightly (<1 mg/l) in the upper part of the metalimnion and then declined throughout the hypolimnion. In 25% of the lakes, oxygen declined continuously throughout the metalimnion and hypolimnion. Eleven percent of the lakes showed a decreased dissolved oxygen concentration in the thermocline (metalimnetic minima), followed by a slight increase, and then a continued decline in the metalimnion and hypolimnion.

I had insufficient data to illustrate a classic lake trout lake having orthograde curves where relatively high dissolved oxygen concentrations persist throughout the summer and fall. For several Minnesota lake trout lakes, however, plots of seasonal changes in the proportion of optimal thermal habitat volume illustrate some of the variation in persistence of dissolved oxygen among lakes (Figures 2-5).

Cruiser Lake (46 ha) in Voyageurs National Park, showed clinograde DTO_2 profiles in 1984. Calculations using Cruiser Lake DTO_2 profiles (L. Kallemeyn, unpublished data 1997) collected from spring through fall show that the volume of optimal thermal habitat for lake trout (i.e., the 12° to 8°C stratum having dissolved oxygen of at least 6.0 mg/l) remained above 11% of total lake volume throughout July and August, and then increased rapidly as the lake cooled, mixed, and was reoxygenated (Figure 2). Of course, the proportion of optimal thermal habitat decreased as the lake continued to cool below 12°C and then 8°C. Seasonal DTO_2 data and THV calculations for Mukooda Lake (309 ha) and Little Trout (97 ha), also in Voyageurs National Park, showed that lake trout habitat conditions were not greatly different from those in Cruiser Lake. The proportions of optimal thermal habitat remained greater than 10% of total lake volume of Mukooda at least into early September in 1997 and 1998. The proportion was at least 6% of total volume for Little Trout Lake in summer 1981. Lake trout apparently had access to optimal thermal and oxygen conditions in at least portions of these lakes throughout the summer and early fall of these years. Dissolved oxygen conditions in Mukooda Lake, however, were slightly less favorable to lake trout from mid-August to late September 1983. During this period, optimum THV_6 declined gradually to about 1% of total lake volume just before fall mixing, however, oxygen did remain greater than 4 mg/l in at least 8% of total lake volume. Stress due to reduced oxygen probably was minimal.

Seasonal DTO_2 data collected in 1999 from Mayhew, West Bearskin, and Birch lakes (Cook County) illustrate contrasting oxygen depletion rates in and below the thermocline (Figures 3, 4, and 5). Of the three lakes, Mayhew Lake had the best summer and fall habitat conditions for lake trout. Conditions in West Bearskin Lake were intermediate in quality relative to Mayhew Lake, while Birch Lake appeared to have poor oxygen conditions for lake trout.

Mayhew Lake (90 ha; Figure 3) showed nearly continuous decline in optimal THV from

Table 2. Lake name, identification number, interpolated mean depth and dissolved oxygen (mg/l) at 12 and 8 °C, lake trout July thermal habitat stratum (THV_6) limited by oxygen: (N = no, Y = yes), mean depth at 6.0, 5.0, and 4.0 mg/l dissolved oxygen for depth-temperature-oxygen profiles measured 1 July - 10 August, 1939-1999, and characterization of July temperature-oxygen depth profiles: C = clinograde; O = orthograde; min = metalimnetic oxygen minima; max = metalimnetic oxygen maxima; na = not applicable.

MN lake number	(*N*)	Mean depth (m) 12°C	8°C	Mean dissolved oxygen conc. (mg/l) 12°C	8°C	JulyTHV_6 oxygen-limited (Y, N)	Mean depth to which oxygen remained ≥ 6 mg/l (m)	5 mg/l (m)	4 mg/l (m)	Characterization of July temperature-oxygen profiles: Oxygen curve type (C,O)	Metalimnetic O_2 min/max.
11-0043	11	7.6	10.5	5.6	3.6	Y	10.7	11.5	11.3	C	variable
16-0041	5	10.5	18.5	8.8	8.3	N	24.4	24.5	24.6	O	max
16-0043	2	9.1	12.7	8.0	7.1	N/Y	18.1	20.1	27.1	C	na
16-0049	5	7.6	10.0	11.2	10.1	N	15.7	17.4	19.0	C	max
16-0077	12	9.8	15.0	8.6	8.1	N	22.8	24.5	24.7	C	na
16-0086	6	8.0	10.9	10.4	9.8	N	29.8	30.0	30.1	O	max
16-0090	2	8.1	10.7	11.1	10.6	N	24.5	24.6	24.7	O/C	max
16-0093	3	9.4	13.2	10.3	10.4	N	52.9	54.3	54.4	O	max
16-0114	4	6.8	9.0	8.0	8.3	Y	13.5	15.9	18.5	O/C	na
16-0135	2	7.0	-	4.9	-	N/Y	6.3	6.6	6.8	O/C	na
16-0139	10	9.0	14.4	11.6	11.5	N	28.1	28.9	29.7	O/C	max
16-0146	8	6.7	10.2	5.9	6.0	N/Y	12.3	15.3	17.1	C	min
16-0147	8	6.8	9.3	10.0	7.6	N/Y	15.5	18.1	19.9	C	max
16-0150	3	7.3	10.9	10.1	8.7	N/Y	20.7	22.8	23.8	C	variable
16-0170	2	6.2	7.9	10.4	6.3	N	7.9	8.6	9.5	C	max
16-0174	1	8.2	-	9.2	-	Y	8.4	8.5	8.5	C	max
16-0188	1	5.8	7.8	10.3	9.3	N	15.6	16.0	16.3	C	max
16-0225	2	4.2	5.4	9.2	8.1	N	12.0	14.2	16.6	C	variable
16-0228	13	8.0	14.8	8.8	7.1	Y	17.5	19.0	20.9	O/C	variable
16-0230	4	7.4	9.8	9.4	7.8	N	17.4	18.4	18.9	C	na
16-0232	4	7.5	9.4	10.7	10.6	N	24.2	28.4	31.1	O/C	max
16-0233	3	5.3	6.7	9.8	8.3	N	10.8	13.4	15.4	C	max
16-0234	1	8.3	10.6	9.4	10.2	N	22.9	24.6	25.8	O	max
16-0239	6	7.6	10.0	5.8	6.7	Y	11.4	12.4	14.1	O/C	min
16-0244	2	9.5	12.7	9.4	9.1	N	-	-	-	C	max
16-0245	1	4.7	6.2	11.9	8.4	N	7.8	10.2	11.1	C	max
16-0247	6	8.1	11.2	4.0	2.1	Y	6.9	7.9	9.2	C	variable
16-0267	1	6.7	9.8	8.0	8.9	N	27.2	27.5	27.8	C	min
16-0268	1	6.7	10.2	7.7	8.9	N	30.1	30.2	30.3	O	na
16-0331	3	8.7	12.0	9.1	8.4	N	-	-	-	O	max
16-0337	7	7.5	10.2	8.6	7.7	N	15.3	17.6	20.4	C	na
16-0354	2	8.6	11.6	7.7	8.4	N	-	-	-	O	min
16-0356	9	11.5	17.1	9.5	9.9	N	-	-	-	O	na
16-0391	2	5.0	6.4	7.9	4.6	Y	6.1	6.6	7.8	C	max
16-0435	2	6.8	9.2	6.3	6.3	N	19.0	21.1	21.4	O	min
16-0448	5	7.8	10.3	9.1	9.2	N	48.1	48.3	48.4	O	max
16-0458	2	4.5	6.5	7.9	7.1	N	12.9	15.0	15.9	C	max
16-0460	3	6.7	11.1	7.2	6.9	N/Y	13.6	17.1	18.4	C	na
16-0461	1	5.7	8.9	4.3	3.3	Y	4.5	4.9	7.3	C	na
16-0463	2	7.6	10.9	12.0	11.3	N	-	-	-	C	max
16-0524	5	6.6	9.6	6.4	6.1	N/Y	13.2	25.0	27.0	O/C	variable
16-0527	1	3.5	4.7	4.1	3.4	Y	1.8	2.6	3.6	C	min
16-0532	1	7.5	9.7	6.1	0.2	Y	7.5	7.7	7.9	C	na
16-0569	3	4.9	6.2	4.5	4.0	Y	3.7	8.5	10.2	C	min
16-0571	4	6.0	8.0	7.4	7.2	N	12.8	19.3	22.9	O/C	na
16-0610	5	8.1	12.6	4.2	2.0	Y	6.6	7.2	8.3	C	na
16-0617	1	7.2	9.6	5.4	3.9	Y	6.4	7.6	11.4	C	na
16-0622	5	9.3	11.9	7.6	5.4	Y	9.7	10.3	12.2	C	na
16-0623	2	9.1	12.6	8.4	7.9	N	29.9	31.7	32.4	O	na

Table 2. Continued.

MN lake number	(*N*)	Mean depth (m) 12°C	Mean depth (m) 8°C	Mean dissolved oxygen conc. (mg/l) 12°C	Mean dissolved oxygen conc. (mg/l) 8°C	JulyTHV_6 oxygen-limited (Y, N)	Mean depth to which oxygen remained ≥ 6 mg/l (m)	Mean depth to which oxygen remained ≥ 5 mg/l (m)	Mean depth to which oxygen remained ≥ 4 mg/l (m)	Characterization of July temperature-oxygen profiles: Oxygen curve type (C,O)	Characterization of July temperature-oxygen profiles: Metalimnetic O_2 min/max.
16-0626	2	8.4	11.0	12.1	11.6	N	14.4	15.4	16.1	C	max
16-0629	6	7.6	11.8	9.0	8.5	N	24.3	25.2	26.1	O/C	variable
16-0633	1	9.5	12.6	5.9	6.5	Y	9.1	18.7	-	O/C	min
16-0673	2	5.9	6.8	8.0	5.3	Y	6.0	7.4	9.5	C	na
16-0686	2	6.6	8.1	6.3	4.9	Y	6.7	7.1	7.4	C	na
16-0716	2	4.7	5.7	7.8	7.0	Y/N	9.4	10.6	14.8	C	max
16-0718	4	7.6	9.7	9.3	7.3	Y	10.7	11.4	12.0	C	variable
16-0723	6	5.9	7.5	8.5	6.5	Y/N	10.0	11.3	13.5	C	max
16-0726	3	5.9	7.4	10.4	8.5	Y/N	9.2	10.0	11.0	C	max
16-0752	4	5.8	7.1	10.2	8.8	N	16.6	21.4	23.8	C	max
16-0753	7	7.3	9.5	9.9	9.0	N	34.9	35.7	35.9	O	max
16-0755	5	4.8	6.1	8.5	8.6	N/Y	21.7	26.4	27.0	O	variable
16-0756	4	5.8	7.2	9.3	7.2	N/Y	8.1	9.5	11.4	C	max
16-0757	1	7.7	9.9	13.2	10.5	N	28.8	29.8	31.0	C	max
16-0759	2	6.0	8.3	8.5	6.7	N	10.6	12.1	13.2	C	na
16-0768	2	7.6	9.4	8.7	8.1	N	26.3	28.2	29.4	O	variable
16-0783	2	5.2	6.7	8.2	5.7	Y/N	6.6	7.7	10.3	C	max
16-0789	3	5.8	7.0	10.4	8.7	N	23.6	26.0	26.8	O/C	max
16-0793	2	5.5	7.1	9.6	7.0	N	10.0	14.9	15.5	C	na
16-0809	3	7.8	11.3	6.4	7.1	Y/N	19.5	31.4	34.2	O	min
16-0811	2	7.1	9.4	8.5	7.6	N	33.0	34.5	35.7	O	max
18-0315	3	8.8	11.8	13.2	10.7	N	28.1	30.3	32.2	C	max
31-0394	1	6.8	9.0	11.6	12.9	N	12.2	12.8	13.4	C	max
31-0395	5	8.7	12.0	12.4	11.9	N	18.7	19.6	20.3	C	max
31-0410	1	10.3	12.7	11.9	11.6	N	19.2	22.0	23.5	C	max
31-0620	4	8.9	11.6	12.3	12.1	N	-	-		O	max
38-0028	1	6.1	7.9	13.4	9.0	N	8.8	9.2	9.5	C	max
38-0065	2	5.2	7.0	4.8	5.3	Y	6.0	6.6	8.2	C	min
38-0113	1	6.2	8.5	6.5	5.6	N	10.1	12.2	13.7	C	na
38-0147	1	6.1	7.7	10.4	9.3	N	9.6	11.8	15.3	C	na
38-0166	4	6.7	8.7	11.3	11.0	N	10.7	11.4	11.9	C	max
38-0168	3	5.1	6.5	11.7	8.9	N	8.4	9.0	9.7	C	max
38-0169	2	4.7	5.7	11.1	8.9	N	9.9	7.9	11.5	C	max
38-0172	2	6.0	7.9	13.4	12.5	N	10.4	11.2	11.8	C	max
38-0178	2	6.3	8.0	9.3	5.8	N/Y	7.9	8.4	9.1	C	max
38-0180	2	6.1	8.0	8.5	6.7	N	13.0	15.9	17.2	C	max
38-0206	2	6.2	7.6	10.9	9.6	N	15.7	17.8	19.5	C	max
38-0207	2	8.2	10.7	14.0	13.6	N	17.4	18.2	18.8	C	max
38-0209	3	6.6	8.4	10.2	8.7	N	10.1	10.6	11.1	C	max
38-0211	3	7.5	9.7	10.7	9.0	N	12.9	14.0	15.1	C	max
38-0214	2	6.2	7.5	13.1	11.7	N	21.4	24.4	26.8	C	max
38-0226	2	9.1	13.2	10.8	10.2	N	48.1	48.2	48.3	O	max
38-0227	6	7.5	10.5	10.8	8.7	N/Y	15.5	-	-	C	max
38-0228	1	6.7	8.6	10.9	10.2	N	16.0	18.8	22.0	C	max
38-0229	4	8.6	10.5	11.1	11.1	N	-	-	-	O	max
38-0351	2	9.0	13.3	9.6	7.5	N/Y	-	-	-	C	na
38-0360	2	4.4	5.4	5.9	4.3	Y	4.4	4.8	8.1	C	na
38-0361	2	5.3	7.0	8.1	7.7	N/Y	-	-	-	C	min
38-0365	2	7.2	9.0	11.9	11.4	N	10.7	11.2	11.7	C	max

Table 2. Continued.

MN lake number	(*N*)	Mean depth (m) 12°C	Mean depth (m) 8°C	Mean dissolved oxygen conc. (mg/l) 12°C	Mean dissolved oxygen conc. (mg/l) 8°C	July THV_6 oxygen-limited (Y, N)	Mean depth to which oxygen remained ≥ 6 mg/l (m)	5 mg/l (m)	4 mg/l (m)	Characterization of July temperature-oxygen profiles: Oxygen curve type (C,O)	Metalimnetic O_2 min/max.
38-0372	2	7.3	12.6	10.3	8.4	N				C	max
38-0386	2	6.8	8.7	11.0	9.2	N	10.6	11.1	11.8	C	max
38-0398	2	7.2	9.1	12.8	11.2	N	13.0	13.3	13.6	C	max
38-0399	2	7.0	9.2	11.7	9.5	N	13.0	12.2	12.5	C	max
38-0400	2	6.8	9.3	8.1	8.7	N				C	min
38-0404S	3	9.9	12.8	11.1	10.7	N				C	variable
38-0404W	1	9.8	12.2	9.8	9.5	N				O	na
38-0404N	1	9.5	11.3	10.1	9.9	N				-	na
38-0408	1	8.0	10.2	10.2	7.3	N	13.7	14.3	15.9	C	max
38-0516	1	7.2	8.7	12.0	9.9	N	10.4	10.8	11.3	C	max
38-0529	6	9.5	13.4	8.5	7.9	Y	26.2	30.2	31.7	O/C	variable
38-0640	7	7.4	10.1	9.0	7.6	N	12.3	15.8	21.6	C	max
58-0123	6	8.4	12.0	7.1	7.7	N				O	min
69-0118	16	8.1	12.5	8.8	8.5	N				O	variable
69-0224E	5	9.7	13.2	6.9	7.8	N					C/Omin
69-0330	2	6.9	8.6	7.4	7.7	N				O	min
69-0369	2	7.0	8.7	10.8	10.4	N	17.7	18.6	19.1	C	na
69-0481	2	7.4	10.5	11.1	7.6	N	11.8	6.6	8.9	C	max
69-0487	2	6.3	7.9	11.0	10.7	N	7.3	11.2	12.4	O/C	max
69-0498	1	13.2	-	6.1	-	Y	18.8	23.2		C	na
69-0682	5	6.3	7.6	9.3	9.7	N	17.6	18.9	19.4	C	max
69-0684	14	8.6	11.8	11.2	9.5	N	15.7	17.2	18.6	C	max
69-0832	3	7.9	10.2	10.9	10.5	N	23.7	24.9	25.6	C	max

mid-June into October, with the proportion of optimal thermal habitat remaining greater than 10% to the end of August, but it declined to almost zero through most of September until fall mixing during the last days of September. Lake trout probably were not greatly stressed in this situation because dissolved oxygen concentration remained greater than 5.0 mg/l throughout the period.

Data from West Bearskin Lake (200 ha) also illustrate clinograde DTO_2 profiles. Oxygen depletion below 6.0 mg/l began in early July, with THV_6 and THV_5 declining to zero before the end of August (Figure 4). THV_4 declined to zero just before fall mixing. Lake trout may have been stressed for a relatively short time at cool temperatures.

Data from Birch Lake (100 ha) also illustrated clinograde DTO_2 profiles, but optimal oxygen conditions for lake trout declined rapidly. The volume of optimal habitat for lake trout declined to zero by 23 July, although the proportion of total lake volume having optimal temperature with oxygen ≥5 mg/l and ≥4 mg/l were approximately 4 and 6% of the total lake volume on that date (Figure 5). By 5 August, however, theoretically there was no water in the 12 to 8°C stratum with even 4 mg/l of dissolved oxygen. Conditions continued to worsen until approximately 27 September at fall mixing. Lake trout were almost certainly more stressed in Birch Lake than in Mayhew and West Bearskin lakes.

Mean depth of lake trout lakes for which dissolved oxygen concentrations ($O_2 \geq 6.0$ mg/l) did not limit lake trout optimum thermal habitat volume tended to be greater than mean depth of lakes for which oxygen was limiting

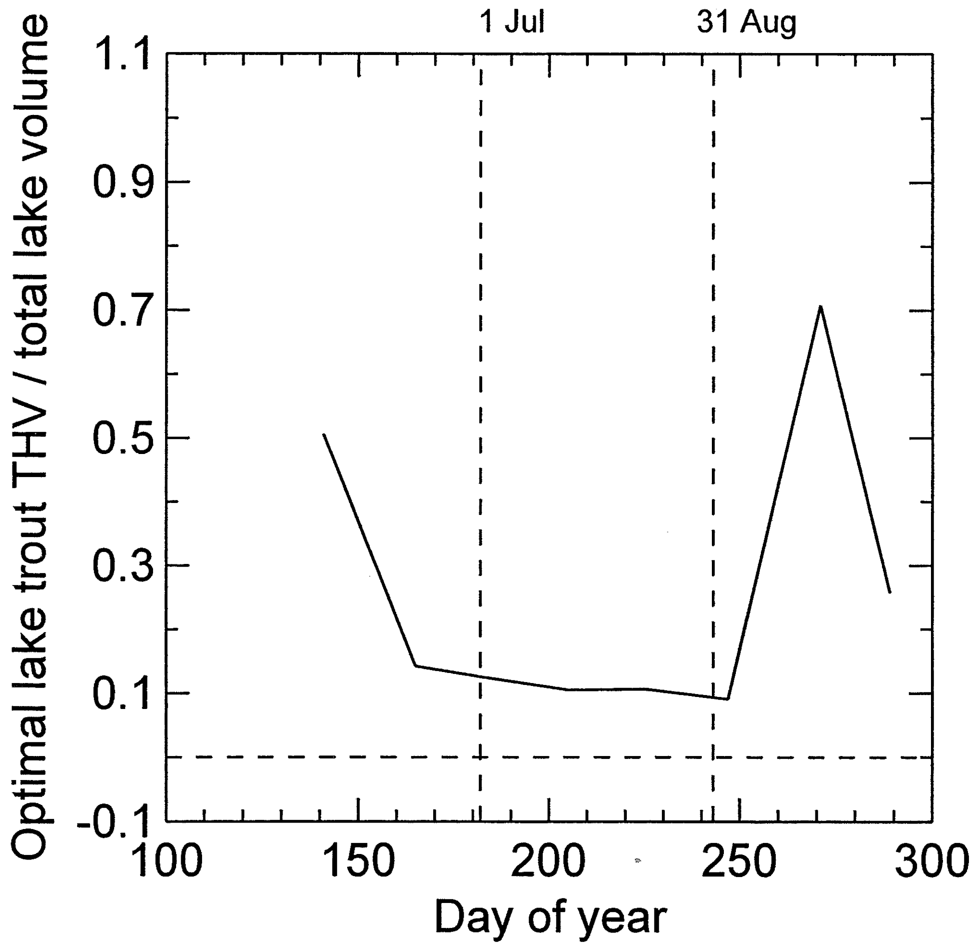

Figure 2. Seasonal changes in the proportion of optimal lake trout thermal habitat volume in Cruiser Lake, Minnesota, 1984.

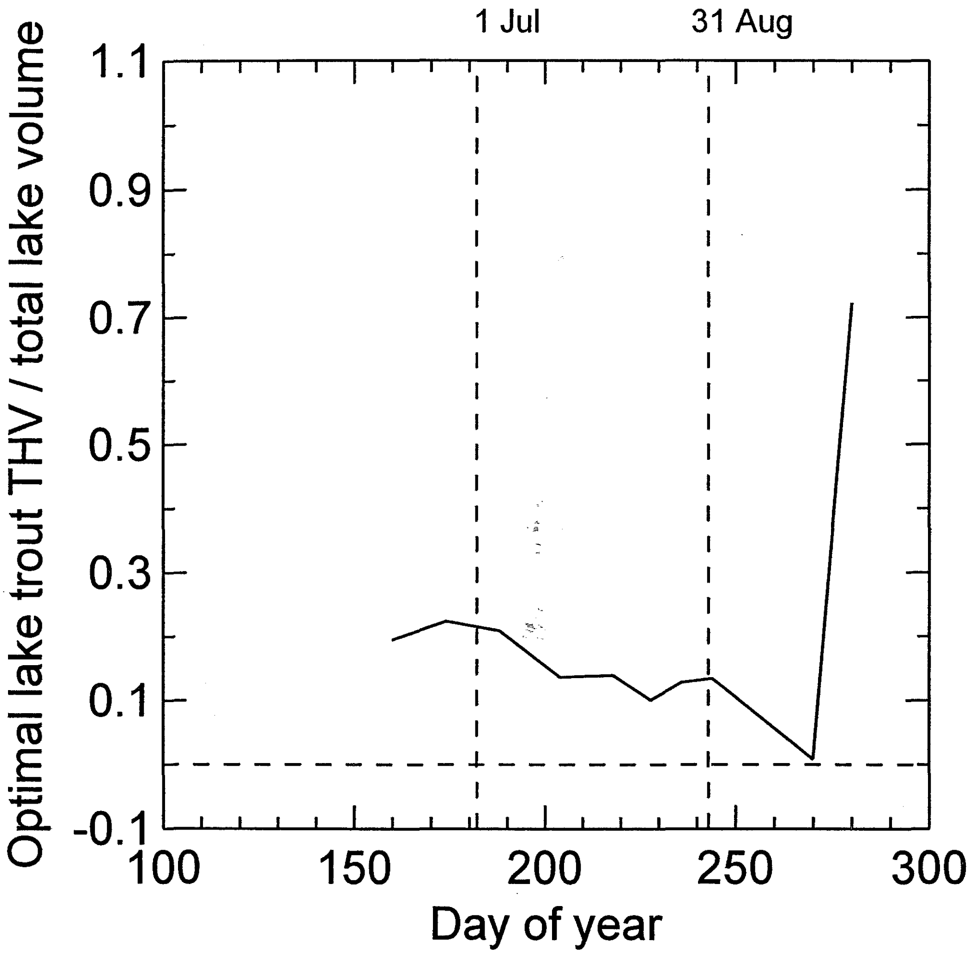

Figure 3. Seasonal changes in the proportion of optimal lake trout thermal habitat volume in Mayhew Lake, Minnesota, 1999.

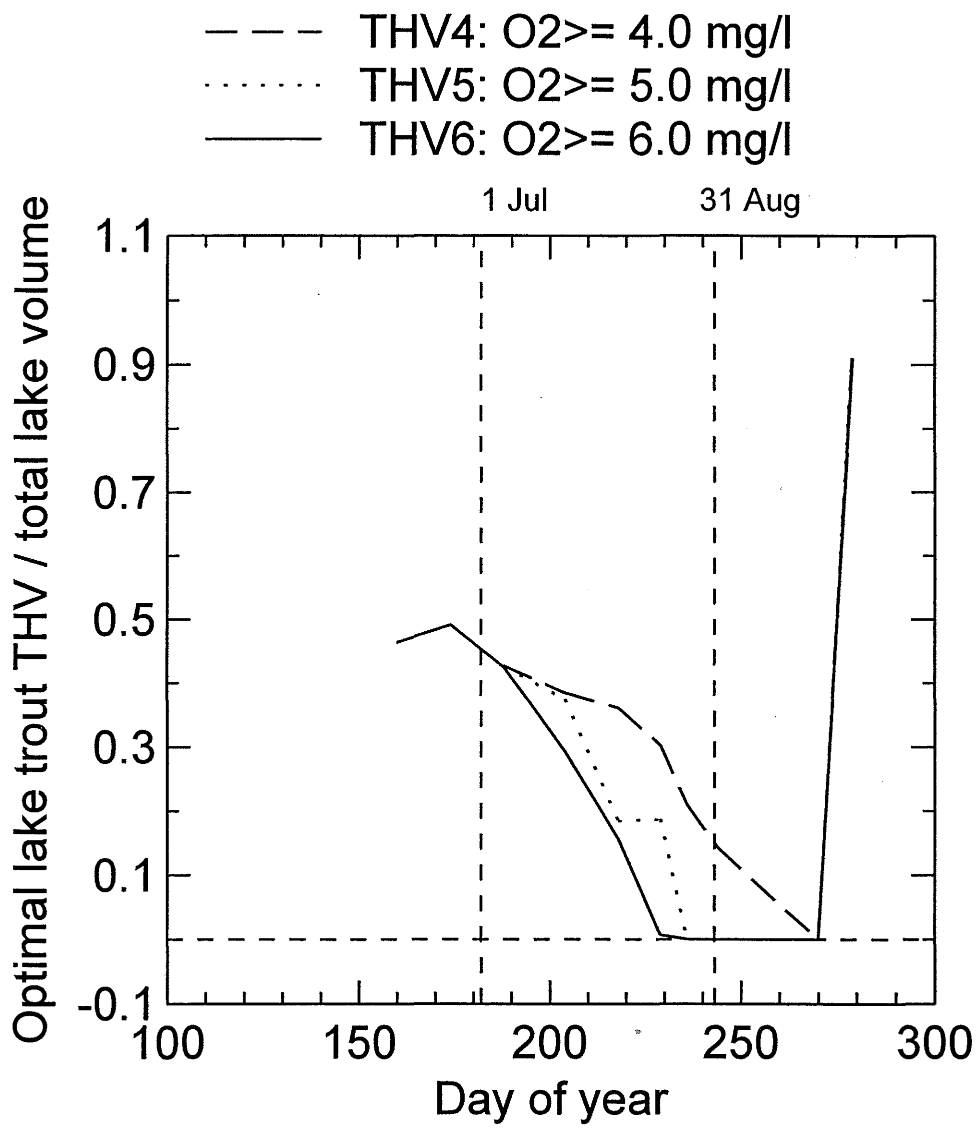

Figure 4. Seasonal changes in the proportion of optimal lake trout thermal habitat volume in W. Bearskin Lake, Cook Cty., Minnesota, 1999.

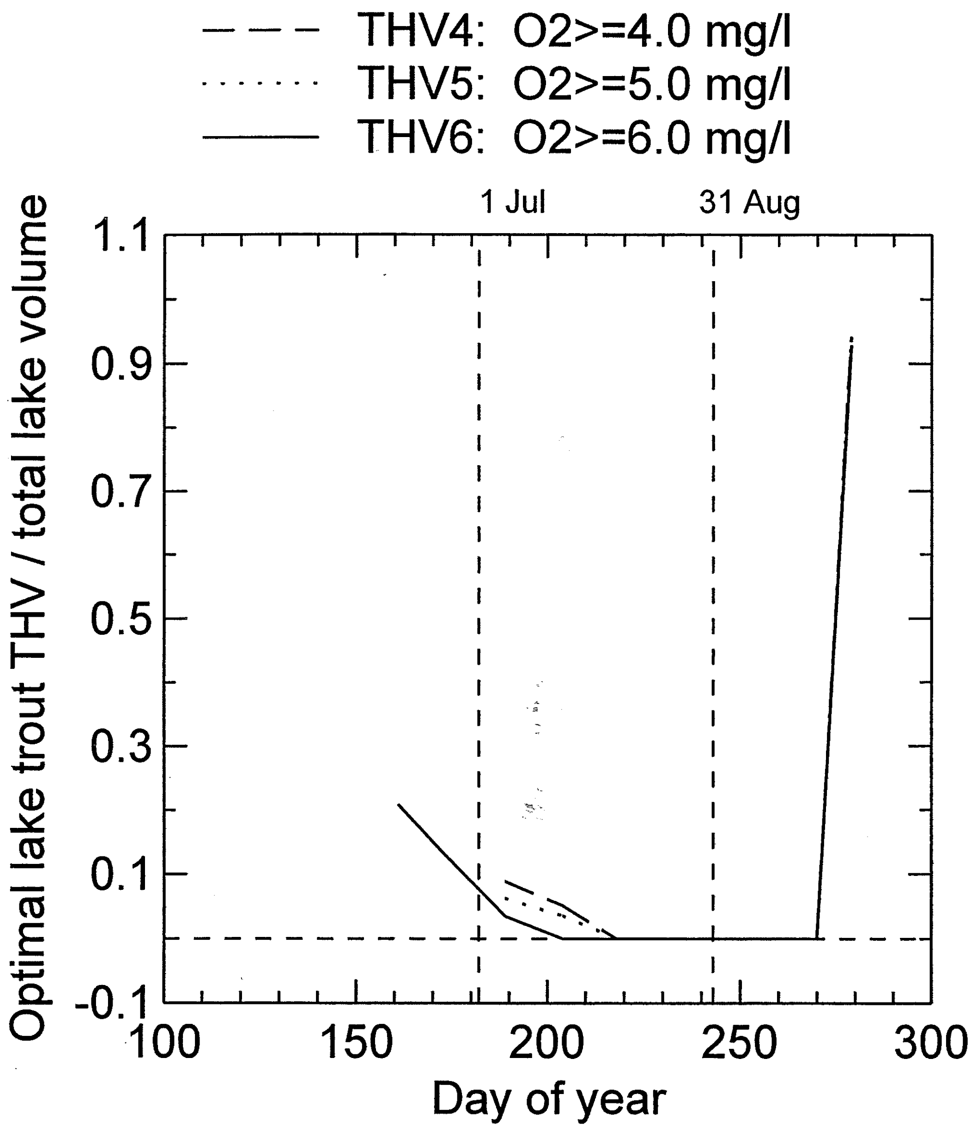

Figure 5. Seasonal changes in the proportion of optimal lake trout thermal habitat volume in Birch Lake, Cook County, Minnesota, 1999.

(O_2 <6.0 mg/l). Dissolved oxygen did not limit optimum THV_6 of approximately 2/3 (N=79) of the lake trout lakes for which mean depth was known (N=118), based on July and early August DTO_2 profiles. Mean depth of these 79 lakes averaged 12.1 m. Dissolved oxygen limited THV_6 in 18% (N=21) of the lakes during the same summer period and their average mean depth was only 7.6 m. Fifteen percent of the lakes (N=18) were intermediate between being oxygen-limited and not limited. Oxygen tended to be non-limiting in 13 of these 18 lakes in July, but was limiting in early August and their average mean depth was 10.2 m. The remaining five lakes tended to be oxygen-limited in most years during this period, but not consistently so. Average mean depth of these five lakes, not surprisingly, was less (8.7 m).

The proportion of optimal lake trout thermal habitat (THV_6 / lake volume) in Minnesota lake trout lakes, based on DTO_2 profiles (1 July - 10 August), averaged only 0.12 of total lake volume (median=0.11) and ranged from 0.0 to 0.51. The range of means for this proportion, calculated by lake, is 0.01 to 0.28 of total lake volume (Table 3).

Potential lake trout yield, predicted from JulyTHV_6 estimates, averaged 1.42 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$ (median=1.44), and varied greatly among small lakes from 0.0 to 3.77 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$ (Figure 6; N=386 estimates from 118 lakes). Means of potential lake trout yields vary considerably among and within lakes, ranging from 0.18 to 3.27 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$ (Table 3). Estimates of zero potential yield occur when no part of the 12° to 8°C stratum has dissolved oxygen ≥6.0 mg/l (i.e., THV_6 =0.0). It should, however, be noted that in some of these lakes there are lake trout populations because there is still some volume of useable lake trout water, provided that dissolved oxygen remains ≥4 mg/l (i.e., THV_5>0.0 or THV_4>0.0). Although some sustainable lake trout yield is likely, or at least possible, in these cases, it is not predicted by the Ontario JulyTHV model.

MEI fish yield (Table 4) of 69 lakes having TDS measurements (not indirect TDS estimates) average 2.30 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$ (range: 1.46 to 4.03) (Figure 7). These values are somewhat less variable than lake trout yields predicted from JulyTHV_6 estimates (Figure 6). MEI lake trout yield (i.e., safe or allowable lake trout yield, which is 25% of potential MEI fish yield average 0.58 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$ (range: 0.37 to 1.01) (Figure 8). For 49 lakes having no TDS measurements, MEI fish yields, derived from estimated TDS and mean depth, average 2.10 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$ (range: 1.29 to 2.81) (Figure 7). Corresponding estimates of MEI lake trout yields for the 49 lakes average 0.53 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$ (range: 0.32 to 0.70) (Figure 8). Actual MEI yields can be estimated for these lakes when TDS measurements become available. The range of MEI lake trout yields is narrower than the range of THV_6 lake trout yields (Table 5). The mean of the MEI lake trout yields is approximately 1/3 of the mean of THV_6 yields.

Winter harvest estimates from lakes in or partially in the BWCAW are few (N=26 lakes), are of mostly historical value (mostly early 1980s), are often based on only one year's information (Table 4), and may be either high or low relative to present harvest levels. Comparison of MEI based (Figure 9a) and THV based (Figure 9b) estimates with winter angling harvest data for lakes in the BWCAW suggests that winter lake trout harvest (Figure 9c) and the corresponding yields generally have been lower than the MEI and usually less than one-half of the THV yield (Table 6). There are, however, exceptions where winter angling yield exceeded the safe MEI yield, but rarely the THV yield. Partridge Lake (44 ha), just inside the BWCAW border, is one of these cases. The average winter lake trout yield (1.9 kg/ha) for 1980 and 1981 (Persons 1985) exceeded the safe MEI lake trout yield for this lake (0.67 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$) by a factor of 2.8 and just surpassed the potential THV yield (1.83 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$). It is doubtful that this yield level is sustainable, but it is not known if it has been maintained over the last 18 years because there have been no subsequent winter creel surveys of the lake. Partridge Lake was one of several lakes, including Trout, Clearwater, Dunn, and Fay lakes, that were thought to receive yearly fishing pressure that may approach or exceed the maximum allowable (approximately 12 angler-hours/hectare)

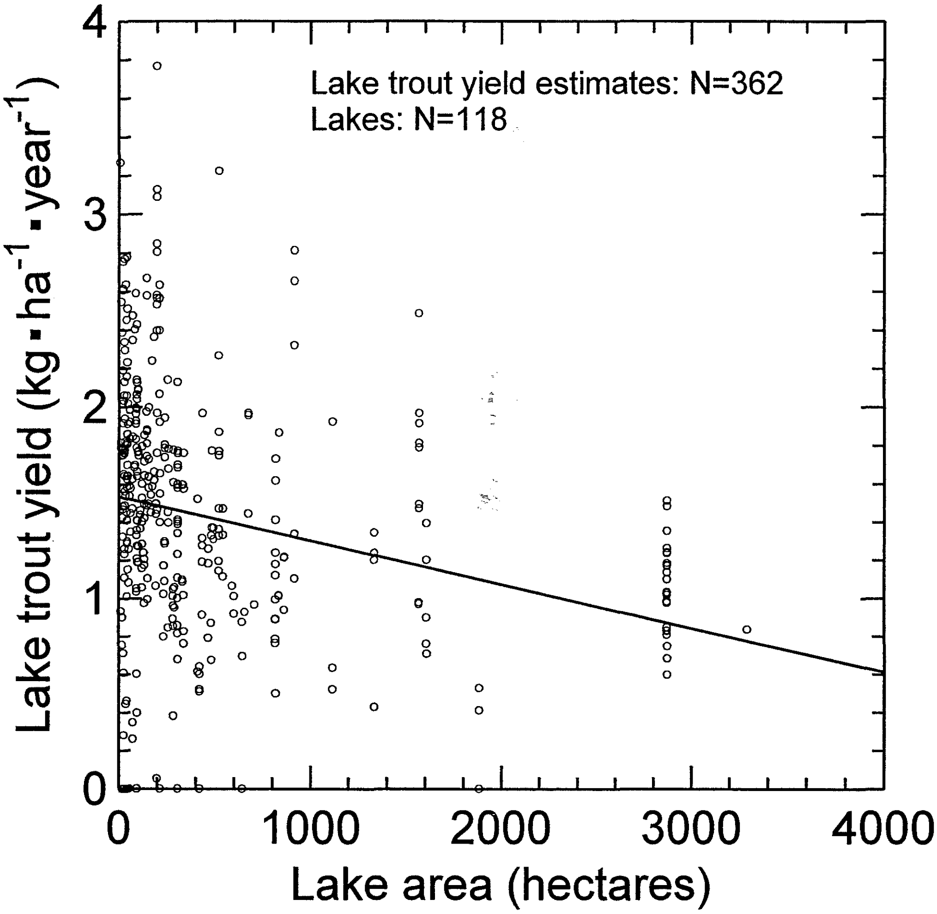

Figure 6. Potential lake trout yield from Minnesota lake trout lakes, based on July thermal habitat volume for lake trout.

Table 3. Summary of estimated lake area, volume, July thermal habitat volume for lake trout (JulyTHV_6), relative THV_6 (JulyTHV_6/total volume), and potential lake trout harvest and yield for Minnesota lake trout lakes based on JulyTHV_6. Depth-temperature-dissolved oxygen profiles from 1 July through 10 August were used to estimate JulyTHV_6. Note: 1 kg/ha = 0.8922 lb/acre.

Lake name	MN lake number	Total area (ha)	Total volume (hm^3)	estimated JulyTHV_6 mean (hm^3)	N	range min.	range max.	Relative THV_6	Harvest (kg/year)	THV_6 yield ($kg \cdot ha^{-1} \cdot year^{-1}$)
Roosevelt	11-0043	600	88.9	8.20	7	-	-	0.066	499.1	0.83
Pine	16-0041	917	153.8	38.36	5	15.77	58.41	0.249	1,875.8	2.04
Moose	16-0043	410	64.5	5.13	2	2.25	8.01	0.079	437.7	1.07
Trout	16-0049	104	10.9	1.36	5	0.83	1.81	0.125	174.2	1.68
Greenwood	16-0077	818	80.8	12.90	12	4.45	20.72	0.159	895.2	1.05
Pike, West	16-0086	285	28.6	3.22	6	0.70	5.91	0.113	315.2	1.10
Crystal	16-0090	85	10.3	1.35	2	1.03	1.67	0.131	174.0	2.05
Mountain	16-0093	836	147.1	17.76	3	12.27	28.66	0.121	1,085.4	1.29
Alder	16-0114	215	19.7	2.44	4	0.00	3.53	0.124	267.1	1.24
Jim	16-0135	24	1.1	0.03	2	0.00	0.05	0.023	10.5	0.43
Clearwater	16-0139	523	79.1	13.93	10	7.54	32.20	0.176	908.6	1.73
Caribou	16-0141	190	11.0	0.53	4	0.00	1.66	0.178	90.2	0.47
Bearskin, East	16-0146	236	15.9	2.13	8	1.29	4.01	0.134	244.8	1.02
Flour	16-0147	134	11.5	1.58	8	0.90	2.18	0.137	194.9	1.45
Daniels	16-0150	186	20.0	3.55	3	2.88	4.78	0.178	349.9	1.87
Trout, Little	16-0170	49	3.6	0.37	2	0.28	0.46	0.103	68.7	1.40
Ram	16-0174	27	1.6	0.02	1	-	-	0.010	7.5	0.28
Kemo	16-0188	74	8.2	0.95	1	-	-	0.117	136.4	1.84
Misquah	16-0225	23	2.2	0.20	2	0.15	0.24	0.089	43.9	1.88
Bearskin, West	16-0228	200	20.4	5.65	13	0.26	10.42	0.277	479.7	2.36
Rose	16-0230	482	54.9	5.37	3	3.22	8.30	0.098	462.0	0.96
Duncan	16-0232	195	27.9	2.47	4	1.71	2.76	0.089	269.2	1.38
Partridge	16-0233	44	4.7	0.45	3	0.37	0.53	0.097	79.7	1.83
Moss	16-0234	100	13.1	1.37	1	-	-	0.105	176.8	1.76
Poplar	16-0239	308	21.4	1.36	6	0.00	3.44	0.063	175.8	0.57
South	16-0244	485	93.1	10.65	2	8.75	12.56	0.114	762.4	1.57
Dunn	16-0245	36	2.7	0.27	1	-	-	0.100	55.6	1.54
Birch	16-0247	100	7.9	0.09	6	0.00	0.53	0.011	25.0	0.25
Vernon	16-0267	95	10.3	1.49	1	-	-	0.146	187.8	1.99
Swan	16-0268	74	10.5	1.44	1	-	-	0.137	183.1	2.48
North	16-0331	1,117	167.2	20.71	3	7.31	45.24	0.124	1,147.1	1.03
Mayhew	16-0337	90	10.1	1.45	7	1.24	2.01	0.144	184.1	2.05
Brule	16-0348	1,884	161.7	3.29	8	0.00	15.44	0.020	330.3	0.18
Winchell	16-0354	332	38.6	5.08	2	3.78	6.39	0.132	448.0	1.35
Gunflint	16-0356	1,570	423.6	60.27	9	27.95	104.36	0.142	2,596.1	1.65
Cone, Middle	16-0391	30	1.4	0.16	1	-	-	0.112	37.8	1.26
Davis	16-0435	147	12.7	2.08	2	1.85	2.32	0.165	238.2	1.62
Cash	16-0438	30	1.9	0.00	1	-	-	-	-	-
Loon	16-0448	436	94.3	7.37	5	4.26	12.48	0.078	580.8	1.33
Town	16-0458	32	3.0	0.44	2	0.36	0.52	0.148	78.1	2.45
Long Island	16-0460	339	27.6	5.82	3	3.48	7.52	0.211	492.0	1.45
Karl	16-0461	44	2.1	0.00	1	-	-	-	-	-
Magnetic	16-0463	176	21.4	3.40	2	2.60	4.21	0.159	336.6	1.91
Cherokee	16-0524	308	32.3	3.80	5	0.00	5.74	0.118	366.3	1.19
Snipe	16-0527	46	2.0	0.00	1	-	-	-	-	-
Blue Snow	16-0532	no map	-	-	0	-	-	-	-	-
Gordon	16-0569	49	3.7	0.00	3	-	-	-	-	-
Frost	16-0571	96	10.2	1.27	4	0.89	1.68	0.124	166.2	1.74
Maraboeuf	16-0610	no map	-	-	0	-	-	-	-	-
Gneiss	16-0617	97	7.8	-	1	-	-	-	-	-

Table 3. Continued.

Lake name	MN lake number	Total area (ha)	Total volume (hm³)	estimated July THV_6 mean (hm³)	N	range min.	range max.	Relative THV_6	Harvest (kg/year)	THV_6 yield (kg·ha⁻¹·year⁻¹)
Alton	16-0622	421	30.0	1.68	5	0.00	2.47	0.056	204.2	0.49
Tuscarora	16-0623	334	36.5	5.08	2	3.74	6.41	0.139	447.3	1.34
Jap	16-0626	48	4.5	0.57	2	0.55	0.59	0.127	94.1	1.96
Seagull	16-0629	1,609	178.3	30.47	5	18.64	48.06	0.171	1,597.7	0.99
Redrock Bay(Sag.)	16-0633	280	16.2	0.48	2	0.00	0.96	0.030	83.8	0.30
Mesaba	16-0673	74	5.5	0.08	2	0.06	0.09	0.014	22.3	0.30
Wine	16-0686	96	3.6	0.05	3	0.00	0.16	0.015	17.5	0.18
Fern	16-0716	23	2.3	0.06	2	0.00	0.12	0.025	18.4	0.19
Fern, West	16-0718	30	3.0	0.27	4	0.23	0.32	0.090	54.7	1.81
Crooked	16-0723	94	7.6	0.60	6	0.00	1.28	0.080	98.4	1.04
Owl	16-0726	33	2.2	0.19	3	0.15	0.24	0.084	42.4	1.30
Bat	16-0752	32	4.2	0.30	4	0.22	0.40	0.071	59.6	1.89
Gillis	16-0753	241	45.8	3.98	7	2.38	5.34	0.087	376.1	1.56
French	16-0755	45	8.0	0.46	5	0.29	0.84	0.057	79.1	1.77
Powell	16-0756	21	1.7	0.13	4	0.06	0.18	0.076	31.8	1.53
Peter	16-0757	102	13.7	1.41	1	-	-	0.104	180.9	1.77
Alpine	16-0759	341	19.5	2.49	2	2.35	2.63	0.128	270.8	0.79
Jasper	16-0768	98	10.5	0.87	2	0.77	0.97	0.083	127.6	1.30
Fay	16-0783	26	2.6	0.16	3	0.05	0.26	0.060	35.9	1.36
Howard	16-0789	62	9.0	0.53	3	0.47	0.59	0.058	89.7	1.46
Red Rock	16-0793	152	10.7	1.18	2	1.10	1.27	0.110	159.1	1.05
Saganaga, Little	16-0809	644	55.2	7.36	3	5.02	10.10	0.133	582.9	0.90
Gabimichigami	16-0811	495	109.8	8.72	2	8.44	9.00	0.079	663.0	1.34
Trout, Big	18-0315	543	84.8	9.62	3	7.68	11.32	0.113	709.2	1.31
Trout, Little	31-0394	29	3.5	0.41	1	-	-	0.119	38.7	1.32
Bluewater	31-0395	147	22.2	3.15	5	2.43	4.19	0.142	318.4	2.16
Trout	31-0410	709	97.5	9.15	1	-	-	0.094	686.2	0.97
Caribou	31-0620	97	14.1	1.64	4	1.20	2.04	0.116	200.1	2.07
Echo	38-0028	19	1.6	0.20	1	-	-	0.121	44.1	2.39
Bone	38-0065	19	1.1	0.02	2	0.00	0.04	0.019	8.7	0.46
Raven	38-0113	83	6.1	0.98	1	-	-	0.161	139.4	1.69
Makwa	38-0147	58	5.3	0.52	1	-	-	0.098	88.5	1.54
Cherry	38-0166	59	7.4	0.74	4	0.69	0.77	0.099	113.5	1.93
Lunar (Moon)	38-0168	23	1.5	0.16	3	0.14	0.20	0.102	37.6	1.62
L. of the Clouds	38-0169	12	0.9	0.06	3	0.03	0.07	0.061	17.4	1.51
Topaz	38-0172	54	3.1	0.33	2	0.29	0.36	0.106	63.3	1.17
Holt	38-0178	44	3.6	0.36	2	0.32	0.40	0.099	67.6	1.53
Ogishkemuncie	38-0180	284	21.4	2.49	2	2.27	2.71	0.117	270.9	0.95
Eddy	38-0187	49	4.7	0.37	2	0.35	0.38	0.078	69.2	1.41
Hanson	38-0206	114	14.4	1.21	3	1.14	1.25	0.084	161.7	1.42
Ester	38-0207	169	17.8	2.26	2	2.16	2.36	0.127	252.8	1.50
Gijikiki	38-0209	46	4.0	0.46	3	0.43	0.49	0.116	81.3	1.79
Cypress	38-0211	468	51.0	6.01	3	3.86	7.39	0.118	504.3	1.08
Rabbit	38-0214	42	5.4	0.31	1	-	-	0.057	60.8	1.45
Kekekabic	38-0226	675	153.7	20.33	3	14.99	23.10	0.132	1,208.8	1.79
Amoeber	38-0227	157	17.7	2.40	6	2.04	3.05	0.136	263.3	1.68
Kek, Little	38-0228	23	4.2	0.30	1	-	-	0.073	60.4	2.61
Knife, Little	38-0229	259	56.2	3.93	4	1.86	5.27	0.070	370.1	1.43
Thomas	38-0351	602	50.6	7.26	2	6.77	7.74	0.143	581.2	0.97
Strup	38-0360	42	3.8	0.06	1	-	-	0.017	19.5	0.46
Wisini	38-0361	38	5.0	0.05	1	-	-	0.010	17.0	0.45
Ahmakose	38-0365	15	1.3	0.13	2	0.10	0.16	0.103	32.6	2.15
Fraser	38-0372	257	22.8	5.31	2	3.91	6.72	0.233	462.0	1.80

Table 3. Continued.

Lake name	MN lake number	Total area (ha)	Total volume (hm^3)	estimated July THV_6 mean (hm^3)	N	range min.	range max.	Relative THV_6	Harvest (kg/year)	THV_6 yield ($kg \cdot ha^{-1} \cdot year^{-1}$)
Sema	38-0386	33	3.3	0.36	2	0.30	0.42	0.108	67.9	2.06
Missionary	38-0398	44	4.7	0.57	2	0.57	0.58	0.121	95.0	2.15
Explorer	38-0399	24	2.4	0.33	2	0.32	0.34	0.136	63.9	2.69
Ima	38-0400	308	36.5	4.08	2	2.40	5.76	0.112	378.6	1.23
Knife, S. Arm	38-0404	864	125.2	14.93	3	11.58	16.65	0.119	970.9	1.12
Knife, N. Arm	38-0404	658	132.2	7.76	1	-	-	0.059	610.2	0.93
Knife, W. Arm	38-0404	592	79.5	8.12	1	-	-	0.102	630.1	1.06
Bear	38-0408	7	0.7	0.08	1	-	-	0.122	23.4	3.27
Ahsub	38-0516	24	23.8	0.18	1	-	-	0.008	42.2	1.75
Snowbank	38-0529	1,335	197.8	29.99	6	7.08	45.80	0.152	1,568.1	1.17
Ojibway*	38-0640	123	11.3	1.33	7	0.89	1.87	0.118	172.3	1.40
Grindstone	58-0123	213	48.5	5.94	6	4.44	6.91	0.123	502.9	2.36
Burntside	69-0118	2,874	351.1	74.26	23	33.12	121.51	0.212	3,028.8	1.05
LacLaCroix*	69-0224	5,967	458.7	41.44	4	36.07	48.28	0.090	1,954.4	0.34
Oyster	69-0330	292	38.8	2.79	2	2.58	3.00	0.071	293.5	1.01
Takucmich	69-0369	131	17.6	1.22	1	-	-	0.069	162.7	1.25
Fat	69-0481	41	2.7	0.63	1	-	-	0.232	101.2	2.44
Gun	69-0487	72	7.8	0.72	2	0.67	0.77	0.092	111.2	1.55
Trout, Big	69-0498	3,294	411.4	64.03	1	-	-	0.156	2,752.7	0.84
Trout, Little	69-0682	98	12.7	0.93	3	0.78	1.19	0.073	134.0	1.37
Mukooda	69-0684	309	37.5	5.80	10	4.00	8.60	0.155	493.2	1.60
Cruiser	69-0832	47	6.1	0.71	2	0.65	0.77	0.114	110.2	2.37

for a sustained yield of lake trout (Schumacher et al. 1966). Estimated winter lake trout yield (1.1 kg/ha) from Explorer Lake (24 ha), for example, which was legally accessible by snowmobile to within less than one mile in 1980 (Heywood 1981), exceeded the MEI lake trout yield (0.55 $kg \cdot ha^{-1} \cdot year^{-1}$), but did not surpass the potential THV yield (2.7 $kg \cdot ha^{-1} \cdot year^{-1}$) for this lake in that year. Since the closure of most snowmobile routes very little creel survey work has been done in the BWCAW, thus current winter angling information is lacking.

Summer (i.e., spring-summer-fall) creel data for lakes in the BWCAW is virtually nonexistent or extremely old (pre-1960). Historical summer lake trout yields (1930s and 1950s) from Seagull Lake averaged 20% of the MEI lake trout yield and only 10% of THV lake trout yield. Summer creel data from 1954-1956 for Clearwater, Mountain, and West Pike lakes (Micklus 1959a,b,c), before the outboard motor ban for most BWCAW lakes, had average summer lake trout yields more than double the THV yield and more than five times the safe MEI yield for West Pike and Mountain lakes, but averaged less than the MEI yield for Clearwater Lake (Table 6). The relatively high yields from Mountain and West Pike lakes, in particular, probably were not sustainable.

Winter and summer yield and harvest estimates for lake trout lakes outside the BWCAW are relatively old (at least 10 years old), with a few exceptions, notably Saganaga (7,120 ha), Gunflint (1,570 ha), Loon (436 ha), and Burntside (2,874 ha) lakes. Saganaga Lake is in the BWCAW, but most of it is legally accessible by motorized boats. Winter harvests from the latter three lakes are lower than the safe MEI lake trout harvest for each lake, as are the combined winter and summer harvest estimates for Saganaga Lake (Table 6). Winter creel survey data from smaller lakes outside the BWCAW, including Kemo (74 ha), Trout (104 ha), Mayhew (90 ha), Birch (100 ha), Moss

Table 4. Morphoedaphic index (MEI= TDS/mean depth; $mg \cdot l^{-1} \cdot m^{-1}$), potential fish yield ($kg \cdot ha^{-1} \cdot year^{-1}$), and potential annual harvest (kg/year) from Minnesota lake trout lakes, exclusive of Lake Superior. Lakes outside the Boundary Waters Canoe Area Wilderness are in **bold** type. Lake names marked with an asterisk (*) denote estimates of MEI yield and MEI harvest derived from estimates of total dissolved solids rather than measured values (see Table 1). Empirical lake trout yield ($kg \cdot ha^{-1} \cdot year^{-1}$) and harvest (kg/season) statistics were adapted from MN DNR "creel survey" reports (various authors and years, see Table 6) and MN DNR Investigational reports (Cook and Younk 1998); (Siesennop 1992). Abbreviations used: W = winter, S = summer.

					Estimated lake trout yield and harvest from various winter and summer creel surveys				
					Yield				Harvest
Lake name	MN lake number	MEI	MEI Yield	MEI Harvest	mean	range	Angling season	*N*	mean
Roosevelt	11-0043	9.70	3.89	2,332.3	0.44	-	W	1	229.1
Pine*	16-0041	1.49*	1.67	1,535.2	no data				
Moose*	16-0043	1.59*	1.72	707.0	no data				
Trout*	16-0049	1.90*	1.87	193.5	0.96	0.36 - 1.76	W	5	99.7
					0.45	0.18 - 0.81	S	6	46.5
Greenwood	16-0077	1.65	1.75	1,434.4	0.09		W	1	-
Pike, West*	16-0086	2.49*	2.11	602.1	2.62	1.12 - 4.04	S	3	756.9
Crystal*	16-0090	1.65*	1.76	149.0	no data				
Mountain*	16-0093	1.42*	1.64	1,370.5	3.40	3.06 - 3.81	S	3	2870.2
Alder*	16-0114	2.74*	2.20	474.0	0.94	-	W	1	-
Jim*	16-0135	3.22*	2.37	57.5	no data				
Clearwater*	16-0139	1.65*	1.76	917.7	0.12	-	W	1	66.1
					0.28	0.11 - 0.54	S	5	149.9
Bearskin, East*	16-0146	3.69*	2.52	594.3	no data				
Flour*	16-0147	2.91*	2.26	303.3	no data				
Daniels	16-0150	2.18	1.99	369.9	0.42	0.18 - 0.54	W	4	104.0
Trout, Little	16-0170	3.70	2.52	124.2	0.43	0.30 - 0.55	W	2	-
Ram	16-0174	4.03	2.62	70.6	0.30	0.22 - 0.37	W	2	-
Kemo*	16-0188	2.27*	2.02	149.6	2.11	-	W	1	-
Misquah	16-0225	2.93	2.27	52.9	no data				
Bearskin, West	16-0228	4.39	2.72	546.2	0.67	0.10 - 1.75	W	9	165.1
					1.26	0.82 - 1.69	S	2	251.2
Rose*	16-0230	3.07*	2.32	1,117.7	no data				
Duncan*	16-0232	2.45*	2.09	408.4	0.15	0.02 - 0.47	W	10	28.4
Partridge	16-0233	4.10	2.64	114.8	1.90	1.66 - 2.14	W	2	-
Moss	16-0234	2.19	1.99	199.4	2.34	1.45 - 3.74	W	3	148.6
Poplar	16-0239	7.48	3.46	1,066.2	no data				
South*	16-0244	1.82*	1.83	889.5	0.45	0.09 - 1.15	W	5	-
Dunn*	16-0245	4.69*	2.81	101.3	no data				
Birch	16-0247	5.33	2.97	296.5	1.46	0.16 - 3.11	W	13	212.3
Vernon	16-0267	1.92	1.88	177.5	no data				
Swan	16-0268	1.66	1.76	130.2	no data				
State*	16-0293	3.42*	2.43	52.1	no data				
North	16-0331	5.28	2.96	3,304.3	0.46	-	S	1	504.8
Mayhew	16-0337	3.19	2.36	212.0	2.02	0.30 - 6.25	W	13	271.2
					0.55	-	S	1	48.3
Brule	16-0348	2.36	2.06	3,884.6	no data				
Winchell*	16-0354	1.73*	1.79	595.1	no data				
Gunflint	16-0356	1.62	1.74	2,731.3	0.34	0.17 - 0.48	W	5	581.8
					0.28	0.11 - 0.45	S	2	469.6
Davis	16-0435	1.31	1.58	233.3	no data				
Cash*	16-0438	3.22*	2.37	71.7	no data				
Loon	16-0448	1.30	1.57	686.1	0.09	0.01 - 0.29	W	4	48.3
Town	16-0458	1.79	1.82	58.0	no data				
Long Island	16-0460	2.32	2.05	692.5	no data				
Karl	16-0461	3.98	2.61	113.6	no data				
Magnetic*	16-0463	2.06*	1.94	340.6	no data				
Cherokee	16-0524	2.20	1.99	615.4	no data				

Table 4. Continued.

Lake name	MN lake number	MEI	MEI Yield	MEI Harvest	Estimated lake trout yield and harvest from various winter and summer creel surveys: Yield mean	Yield range	Angling season	*N*	Harvest mean
Snipe	16-0527	5.94	3.12	142.8	no data				
Blue Snow	16-0532	no depth map			no data				
Gordon	16-0569	2.34	2.05	100.6	no data				
Frost	16-0571	2.11	1.96	187.4	no data				
Maraboeuf	16-0610	no depth map			no data				
Gneiss*	16-0617	3.09*	2.33	226.0	no data				
Alton*	16-0622	2.81*	2.23	937.5	no data				
Tuscarora	16-0623	2.11	1.96	653.5	0.30	0.01 - 0.52	W	4	-
Jap*	16-0626	2.14*	1.97	94.5	no data				
Seagull*	16-0629	2.25*	2.02	3,247.1	0.10	0.08 - 0.12	S	3	168.3
Saganaga	16-0633	3.72	2.53	18,192.1	0.12	0.06 - 0.17	S	2	813.3
					0.23	0.13 - 0.34	W	3	1670.7
Redrock Bay*	16-0633	4.32*	2.70	755.8	no data				
Mesaba*	16-0673	2.02*	1.92	141.3	no data				
Wine*	16-0686	4.00*	2.61	251.8	no data				
Fern	16-0716	2.19	1.99	45.4	no data				
Fern, West	16-0718	2.19	1.99	60.3	no data				
Virgin	16-0719	3.38	2.42	55.3	no data				
Crooked	16-0723	3.02	2.30	217.1	no data				
Owl	16-0726	3.18	2.36	76.6	no data				
Bat	16-0752	1.47	1.66	52.6	no data				
Gillis	16-0753	1.21	1.52	366.4	no data				
French	16-0755	1.23	1.54	68.7	no data				
Powell	16-0756	2.48	2.11	43.8	no data				
Peter*	16-0757	1.38*	1.62	165.2	no data				
Alpine*	16-0759	4.19*	2.67	909.6	no data				
Jasper*	16-0768	2.35*	2.06	202.4	no data				
Fay	16-0783	2.19	1.99	52.6	no data				
Howard*	16-0789	1.49*	1.68	103.2	no data				
Red Rock*	16-0793	3.54*	2.47	374.9	no data				
Saganaga, Little	16-0809	2.58	2.14	1,382.4	no data				
Gabimichigami*	16-0811	0.83*	1.29	636.5	no data				
Big Trout	18-0315	10.51	4.03	2,190.3	0.27	0.07 - 0.10	S	1	156.9
					0.83	-	W	1	478.6
Trout, Little*	31-0394	11.08*	4.12	121.6	no data				
Bluewater	31-0395	9.83	3.91	576.6	no data				
Trout	31-0410	9.60	3.87	2,747.4	0.09	-	S	3	61.1
Caribou	31-0620	2.60	2.15	207.9	0.65	0.25 - 1.23	W	4	62.8
Raven*	38-0113	3.39*	2.42	200.3	no data				
Makwa	38-0147	2.49	2.11	121.6	no data				
Cherry*	38-0166	1.98*	1.90	111.9	0.13		W	1	7.7
Lunar (Moon)*	38-0168	3.74*	2.53	58.7	no data				
L. of the Clouds*	38-0169	3.23*	2.37	27.4	no data				
Topaz*	38-0172	4.41*	2.73	147.5	0.0	-	W	1	0.0
Holt*	38-0178	2.45*	2.10	92.9	0.12	-	W	1	5.4
Ogishkemuncie*	38-0180	2.05*	1.93	549.5	no data				
Hanson	38-0206	3.19	2.36	268.2	0.59	-	W	1	68.5
Ester	38-0207	3.38	2.42	409.1	0.57	-	W	1	88.9
Gijikiki	38-0209	3.97	2.61	118.5	no data				
Cypress	38-0211	6.23	3.19	1,492.2	0.01	-	W	1	3.2

Table 4. Continued.

Lake name	MN lake number	MEI	MEI Yield	MEI Harvest	Estimated lake trout yield and harvest from various winter and summer creel surveys: Yield mean	Yield range	Angling season	*N*	Harvest mean
Rabbit	38-0214	2.43	2.09	87.4	0.15	-	W	1	6.4
Kekekabic*	38-0226	0.83	1.29	869.8	0.18	-	W	1	117.5
Amoeber*	38-0227	2.22*	2.00	314.0	0.05	-	W	1	6.4
Kek*	38-0228	1.61*	1.73	40.2	no data				
Knife, Little	38-0229	2.95	2.28	591.1	0.46	-	W	1	119.7
Thomas	38-0351	2.35	2.06	1,239.0	no data				
Strup*	38-0360	2.80*	2.22	93.8	no data				
Wisini*	38-0361	1.91*	1.87	71.3	no data				
Ahmakose	38-0365	2.29	2.03	30.9	no data				
Fraser	38-0372	2.21	2.00	514.2	no data				
Sema (Coon)*	38-0386	2.48*	2.11	69.5	no data				
Missionary	38-0398	2.72	2.20	97.0	0.39	-	W	1	16.8
Explorer	38-0399	2.76	2.21	52.6	1.09	-	W	1	25.9
Ima (Slate)	38-0400	1.71	1.78	549.4	no data				
Knife: all	38-0404	3.09	2.32	4,901.7	0.43	-	W	1	904.9
South Arm	38-0404	3.31	2.40	2,074.1	-				
West Arm	38-0404	3.58	2.49	1,471.7	-				
North Arm	38-0404	2.39	2.07	1,361.9	-				
Ahsub	38-0516	3.12	2.34	56.2	no data				
Snowbank	38-0529	1.26	1.55	2,075.7	0.35	0.07 - 0.65	W	6	647.0
Ojibway*	38-0640	4.36*	2.72	333.4	0.32	0.05 - 0.66	W	5	44.2
Grindstone	58-0123	3.78	2.55	542.2	0.16	0.01 - 0.29	S	4	34.4
Burntside	69-0118	2.77	2.22	6,367.4	0.19	0.10 - 0.29	W	6	499.1
Lac La Croix (east half only)*	69-0224	3.26*	2.38	14,209.3	no data				
Oyster	69-0330	1.28	1.56	456.6	no data				
Takucmich	69-0369	1.11	1.47	191.8	no data				
Fat*	69-0481	2.26*	2.02	83.4	no data				
Gun*	69-0487	1.37*	1.62	116.1	no data				
Trout, Big	69-0498	2.56	2.14	7,039.6	no data				
Trout, Little	69-0682	1.69	1.77	172.6	no data				
Mukooda	69-0684	3.13	2.34	721.1	no data				
Cruiser	69-0832	1.28	1.56	72.6	no data				

Table 5. Summary of lake trout yield estimates developed from July thermal habitat volume (JulyTHV_6), MEI lake trout yields, and MEI fish yields for Minnesota lake trout lakes. July THV_6 yield estimates were calculated from 362 depth-temperature-oxygen profiles. Note: For lakes having no actual TDS measurements, estimates of MEI lake trout yields and estimates of MEI fish yields were calculated from estimates of TDS (see methods). MEI = morphoedaphic index (i.e., TDS/mean depth); TDS = total dissolved solids (mg/l); na = not applicable.

Metric	Yield ($kg \cdot ha^{-1} \cdot year^{-1}$): July$THV_6$ lake trout yield	MEI lake trout yield	Estimated MEI lake trout yield	MEI fish yield	Estimated MEI fish yield
Lakes (*N*)	118	69	49	69	49
mean	1.51	0.58	0.53	2.30	2.10
minimum	0.00	0.37	0.32	1.46	1.29
maximum	3.77	1.01	0.70	4.03	2.81
TDS	na	measured	estimated	measured	estimated

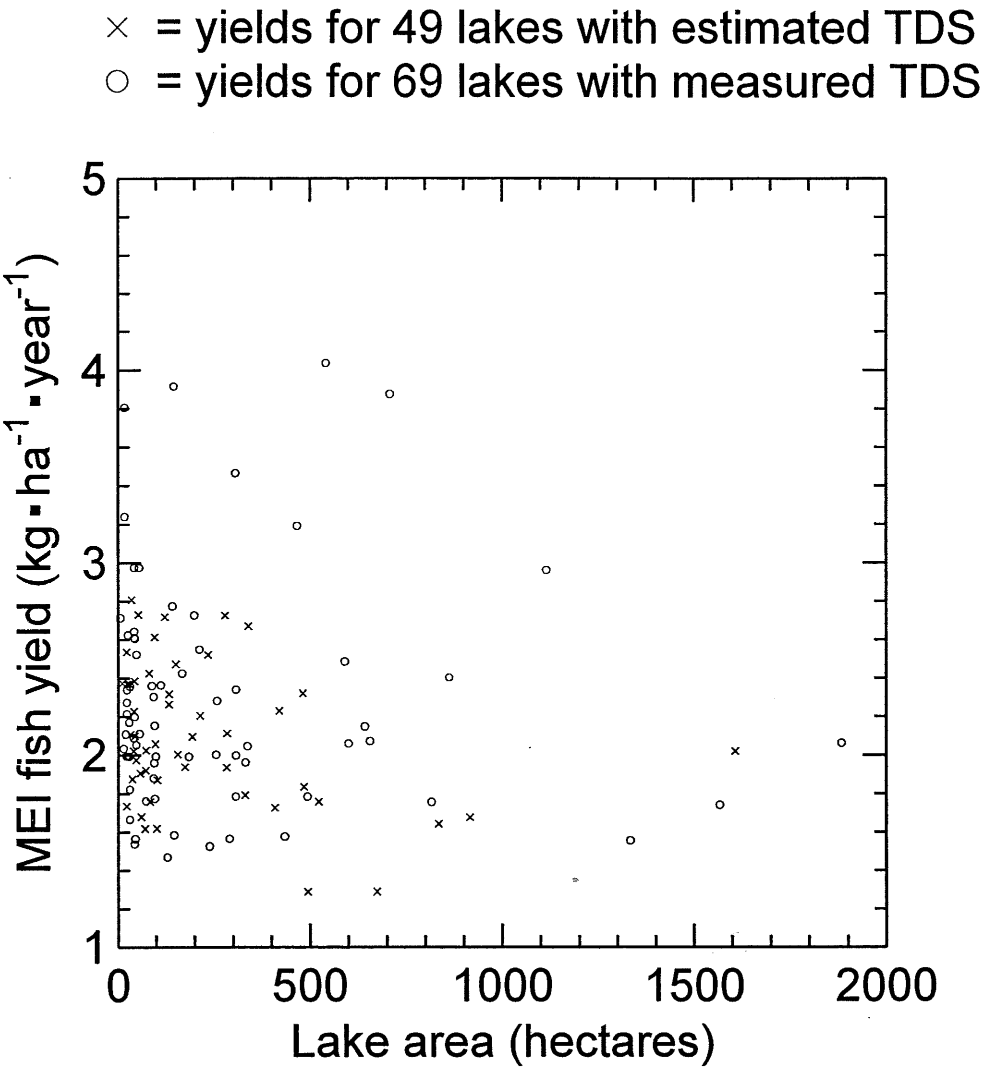

Figure 7. Potential MEI fish yield from 118 Minnesota lake trout lakes, based on morphoedaphic index (MEI = TDS/mean depth).

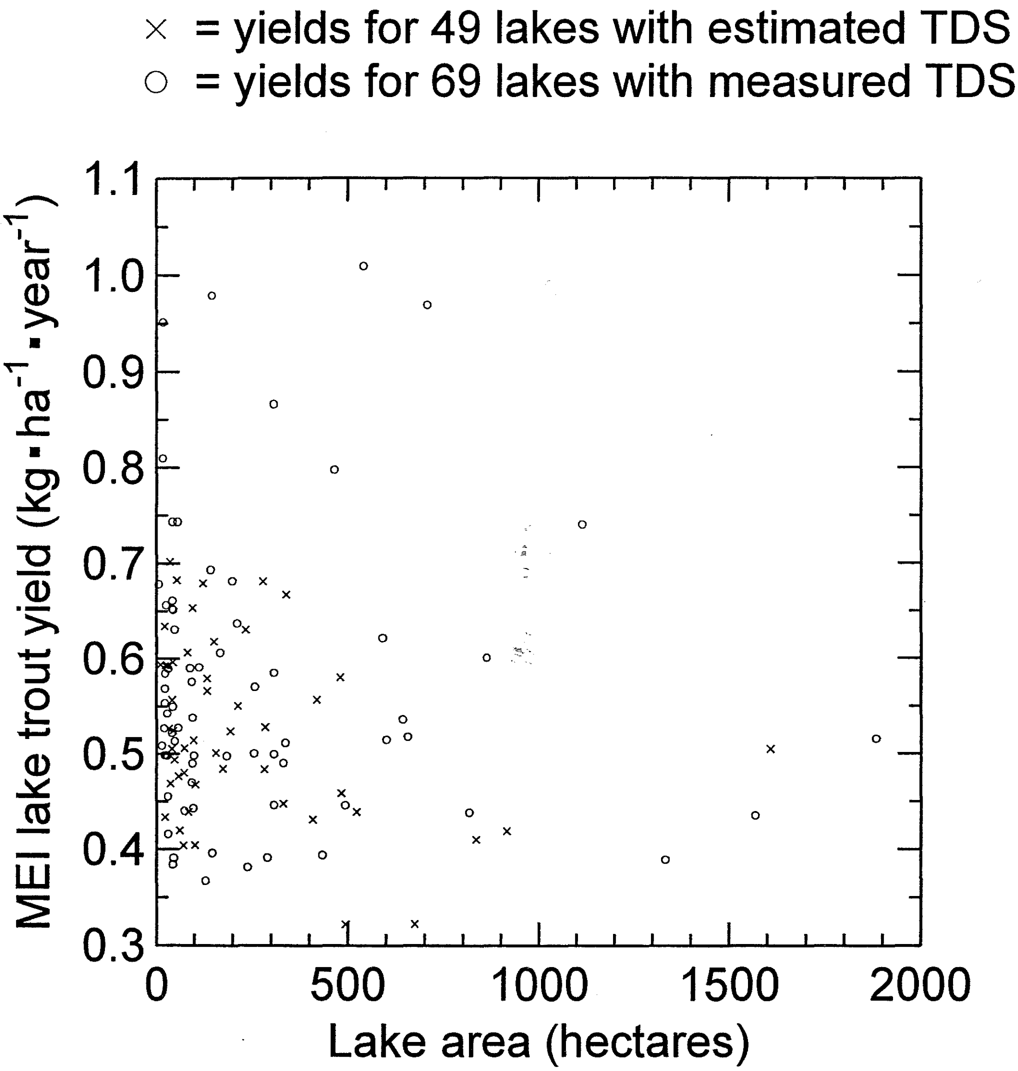

Figure 8. MEI lake trout yields derived from potential MEI fish yield estimates for 118 Minnesota lake trout lakes.

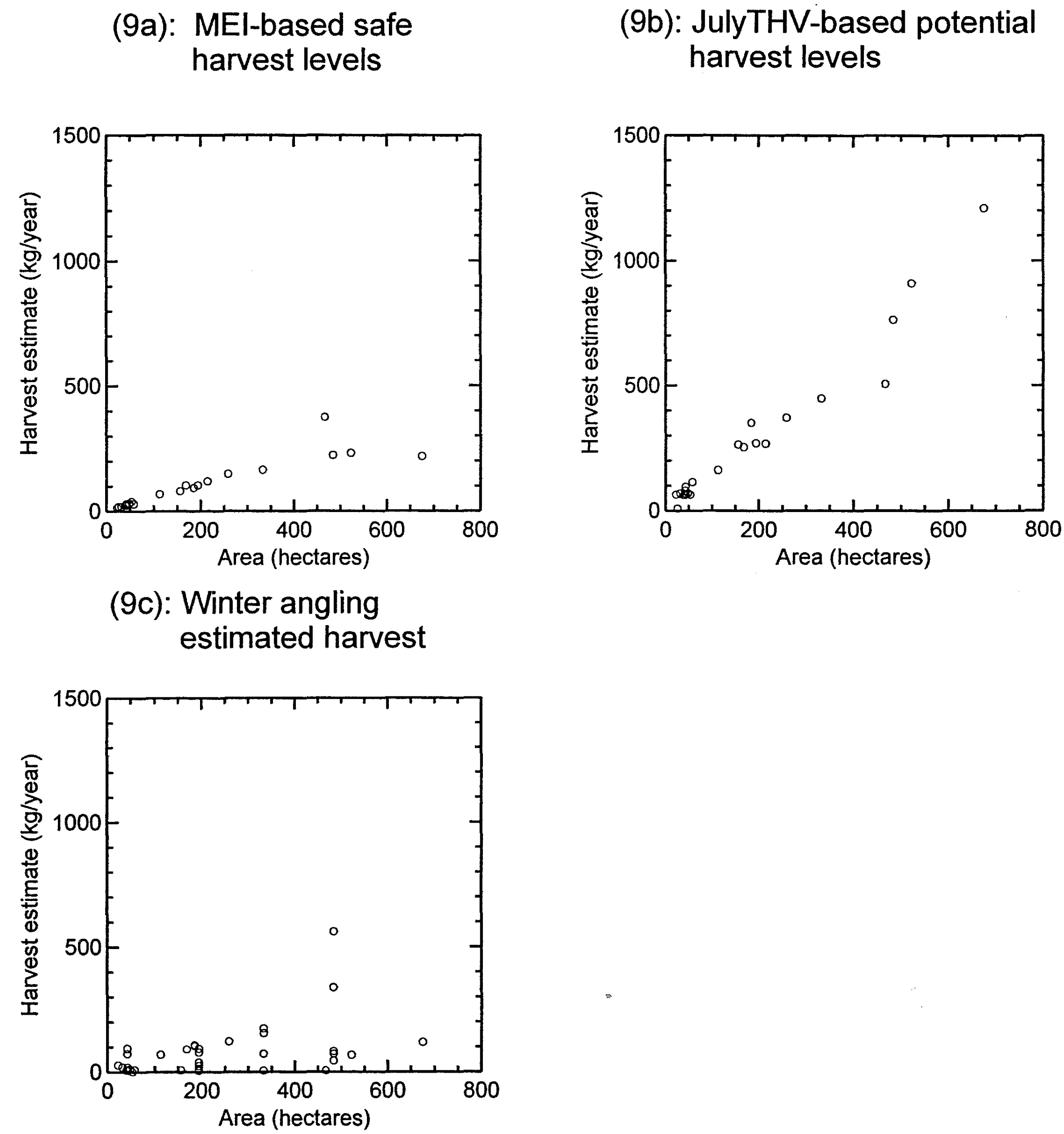

Figure 9 a, b, c. MEI-based and THV-based estimates of potential lake trout harvest and estimated winter angler harvest of lake trout from lakes within the Boundary Waters Canoe Area Wilderness. Most winter creel surveys date from 1980-1984 and most harvest estimates are based on one winter's data.

Table 6. Comparison of lake trout yield estimates derived from winter and summer creel surveys (Table 4) with potential lake trout yield (Table 3) derived from July thermal habitat volume (THV), and MEI lake trout yield (Table 4) for lakes in or out of the Boundary Waters Canoe Area Wilderness, 1936-1996. Note: Cases where THV or MEI yield was approached or exceeded by empirical lake trout yield estimates (derived from winter or summer creel survey data) are underlined. (*N*) denotes the number of lake trout yield estimates that were averaged. Lake trout angling yield estimates derived from data older than 1986 (Appendix Table 1) are shown in **bold** type. Lakes whose management included lake trout stocking prior to or during the creel survey period are shown in **bold** type.

Lake name	MN lake number	Average yield (kg/ha) Winter (*N*)		Summer (*N*)		Creel survey year(s)	Potential yield estimates ($kg \cdot ha^{-1} \cdot year^{-1}$) THV yield	MEI LAT yield
				Lakes in or partially in the BWCAW				
Pike, West	16-0086	—		**<u>2.62</u>**	(3)	1954-1956	<u>1.10</u>	<u>0.53</u>
Mountain	16-0093	—		**<u>3.40</u>**	(3)	1954-1956	<u>1.29</u>	<u>0.41</u>
Clearwater	16-0139	0.12	(1)	0.28	(5)	1985;1954-97	1.73	0.44
Daniels	16-0150	**<u>0.42</u>**	(4)	---		1980-85, 1991	1.87	<u>0.50</u>
Trout, Little	16-0170	**0.43**	(2)	---		1980-1981	1.40	0.63
Ram	16-0174	**0.30**	(2)	---		1980-1981	0.28	0.66
Duncan	16-0232	0.15	(10)	---		1980s	1.38	0.52
Partridge	16-0233	**<u>1.90</u>**	(2)	---		1980-1981	<u>1.83</u>	<u>0.67</u>
South	16-0244	**<u>0.45</u>**	(5)	---		1970s-80s	1.57	<u>0.46</u>
Tuscarora	16-0626	**0.30**	(4)	---		1970s-80s	1.34	0.49
Seagull	16-0629	---		**0.10**	(3)	1936,'56,'57	0.99	0.51
Saganaga	16-0633	0.23	(3)	0.12	(4)	1984-1996	na	0.63
Cherry	38-0166	**0.13**	(1)	---		1980	1.93	0.48
Topaz	38-0172	**0.00**	(1)	---		1980	1.17	0.68
Holt	38-0178	**0.12**	(1)	---		1980	1.53	0.53
Hanson	38-0206	**<u>0.59</u>**	(1)	---		1980	1.42	<u>0.59</u>
Ester	38-0207	**<u>0.57</u>**	(1)	---		1980	1.50	<u>0.61</u>
Cypress	38-0211	**0.01**	(1)	---		1980	1.08	0.80
Rabbit	38-0214	**0.15**	(1)	---		1980	1.45	0.52
Kekekabic	38-0226	**0.18**	(1)	---		1980	1.79	0.32
Amoeber	38-0227	**0.05**	(1)	---		1980	1.68	0.50
Knife, Little	38-0229	**<u>0.46</u>**	(1)	---		1980	1.43	<u>0.57</u>
Missionary	38-0398	**0.39**	(1)	---		1980	2.1	0.55
Explorer	38-0399	**<u>1.09</u>**	(1)	---		1980	2.69	<u>0.55</u>
Knife	38-0404	**<u>0.43</u>**	(1)	---		1980	1.04	<u>0.58</u>
Snowbank	38-0529	**<u>0.35</u>**	(6)	---		1973-75,'84,'91	1.17	<u>0.39</u>
				Lakes outside the BWCAW				
Roosevelt	11-0043	0.44	(1)	---		1995	0.83	0.97
Trout	16-0049	**<u>0.96</u>**	(5)	**<u>0.45</u>**	(6)	various	<u>1.68</u>	<u>0.47</u>
Kemo	16-0188	**<u>2.11</u>**	(1)	---		1984	<u>1.84</u>	<u>0.51</u>
Bearskin, West	16-0228	<u>0.67</u>	(9)	<u>1.26</u>	(2)	1980s	<u>2.36</u>	<u>0.68</u>
Moss	16-0234	**<u>2.34</u>**	(3)	---		1980s	<u>1.76</u>	<u>0.50</u>
Birch	16-0247	<u>1.46</u>	(13)	---		1980s	<u>0.25</u>	<u>0.74</u>
North	16-0331	---		0.46	(1)	1992	1.03	0.74
Mayhew	16-0337	<u>2.02</u>	(13)	<u>0.55</u>	(1)	1970-1990	<u>2.05</u>	<u>0.59</u>
Gunflint	16-0356	0.34	(5)	0.28	(2)	1980-93;1983,'92	1.65	0.44
Loon	16-0458	0.09	(4)	---	(1)	1980-93; 1986	1.33	0.39
Big Trout	18-0315	<u>0.83</u>	(1)	**<u>0.27</u>**	(1)	1995; 1988	1.31	<u>1.01</u>
Trout	31-0410	---	(1)	**0.09**	(3)	1982;1982-84	0.97	0.97
Caribou	31-0620	**<u>0.65</u>**	(4)	---		1979-1982	2.07	<u>0.54</u>
Ojibway	38-0640	**0.32**	(5)	---		1973-1984	1.40	0.68
Grindstone	58-0123	---		**0.16**	(4)	1960s, 1985	2.36	0.64
Burntside	69-0118	**0.19**	(6)	---		1970s, '84, '92	1.05	0.56

(100 ha), and West Bearskin (200 ha) lakes, dates from the 1970s - 1990. Estimated angler harvest of lake trout from these six Cook County lakes (Figure 10c) was generally greater than the MEI or THV based potential harvest (Figures 10 a, b). Lake trout harvest from Trout Lake, which is routinely stocked with rainbow trout *Oncorhynchus mykiss*, but was very infrequently stocked with lake trout, was often greater than either the MEI and THV based lake trout harvest. This population may be over exploited. The latter four lakes were stocked with relatively large numbers of yearling lake trout (approximately 18 months old) on a regular basis for maintenance of a popular fishing lake or as part of research studies. Similarly, Kemo Lake is regularly stocked with fall fingerlings (approximately nine months old) to maintain a popular, relatively accessible lake trout fishery outside the BWCAW. In 1984, lake trout yield from Kemo Lake in winter exceeded THV and MEI lake trout yields (Table 6), but it is not known if this yield (2.1 $kg \cdot ha^{-1} \cdot year^{-1}$) is typical for this lake. As stocked cohorts recruit to these fisheries, winter and summer anglers focus their efforts on the lakes and angling pressure (angler-hours/hectare) and yield, probably unsustainable without stocking, fluctuate accordingly (Siesennop 1992). A similar pattern was observed for Duncan Lake (200 ha) just inside the BWCAW. The few data points (Figures 11a, b, and c), mostly from the early 1960s and through the 1980s, estimated summer harvest of lake trout generally at or below the MEI and THV derived harvest levels, especially for the larger lakes.

Discussion

Estimates of the amount of optimal thermal habitat, as defined by Payne et al. (1990), provide a direct measure of habitat stress and an indirect measure of potential lake trout yield. The MEI model (Ryder 1965) gives an independent indirect estimate of potential fish yield, while 25% of the MEI yield has been suggested as a safe lake trout yield for Ontario lakes (OMNR 1982). Current angler use, harvest, lake trout abundance, and habitat information is needed to evaluate the status of lake trout populations in and out of the BWCAW.

The majority (67%) of Minnesota's lake trout lakes do not appear to have serious oxygen depletion in July and early August based on available DTO_2 profiles. More detailed knowledge of oxygen conditions later in August and September, however, no doubt would add lakes to the group showing significant oxygen depletion prior to cooling and fall mixing. Oxygen limits the volume of optimum thermal habitat for lake trout in at least 1/3 of Minnesota's lake trout lakes in early fall. Therefore, some lake trout populations probably are stressed, in that, behavior, growth, and reproduction may be adversely affected (Evans et al. 1991). In some lakes at certain times of the year, lake trout exist in physical conditions that may not be conducive to long term survival. Ryan and Marshall (1994) found that natural lake trout populations seldom occur in northwestern Ontario lakes in which seasonal oxygen depletion exceeds 40%, but were usually found in lakes for which oxygen depletion was predicted to be less than 20% with a transition between these depletion levels. In Minnesota, more DTO_2 profiles taken throughout the year may be needed to document oxygen depletion and year-to-year variation in optimum THV.

The seasonal DTO_2 and THV changes in Cruiser, Mukooda, and Little Trout lakes in northern St. Louis County and those of Mayhew, West Bearskin, and Birch lakes in Cook County probably are typical of what would be found in many of Minnesota's small-to-medium-size lake trout lakes. Some remote lakes that are believed to have lake trout populations have DTO_2 conditions considered marginal for long term lake trout survival. Lakes that have a mean depth less than 6 m are likely to have less than optimum habitat conditions for lake trout (MacLean et al. 1990). Ten percent of Minnesota's lake trout lakes are in this depth category. Another five percent of Minnesota's lake trout lakes have mean depths less than 7 m. Poplar and East Bearskin are two lakes are in this category. It is not known if re-introduced lake trout populations will be self-sustaining in

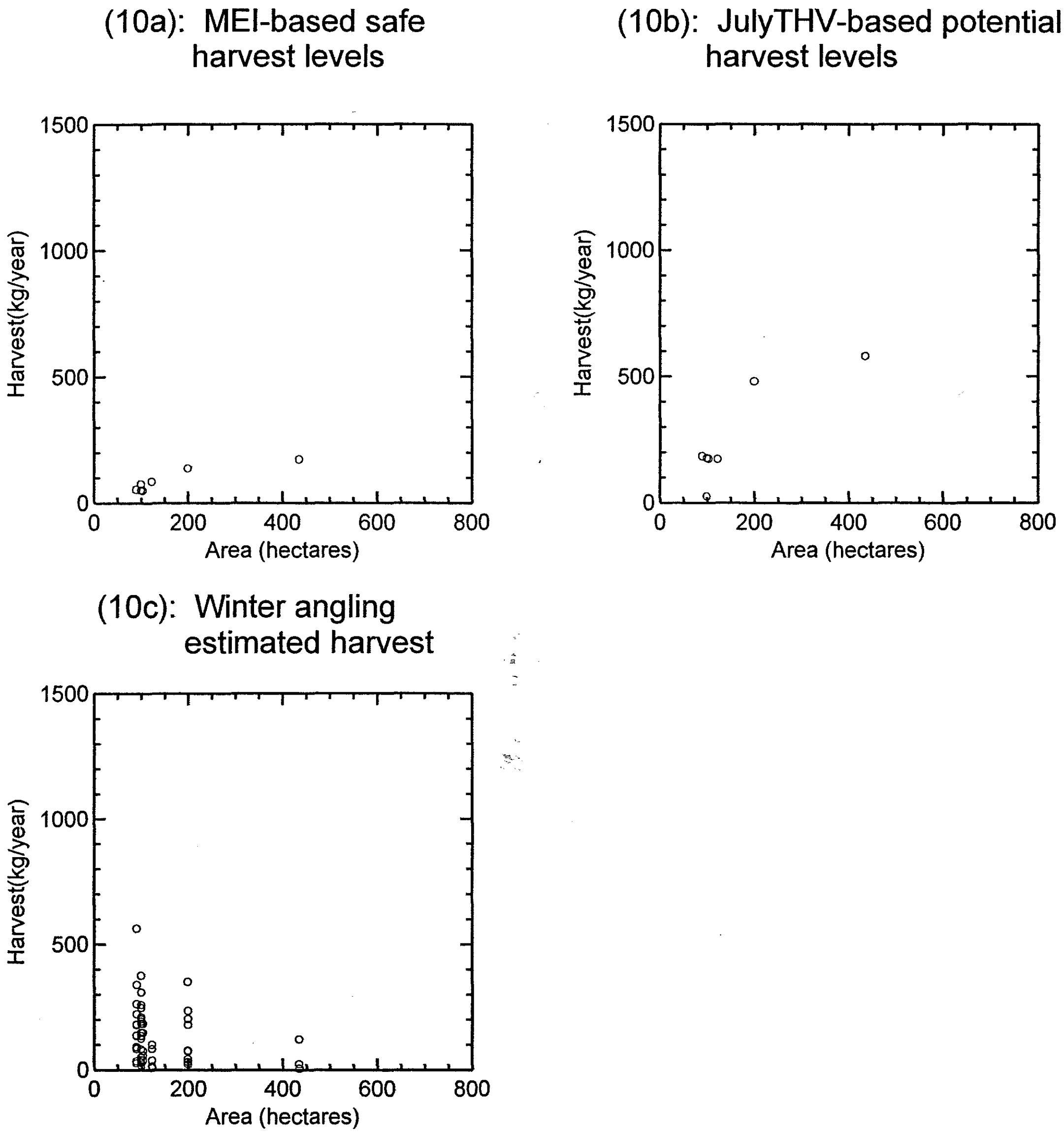

Figure 10 a, b, c. MEI-based and THV-based estimates of potential lake trout harvest and estimated winter angler harvest of lake trout from lakes outside the Boundary Waters Canoe Area Wilderness. Most winter creel surveys dates range from 1973-1997.

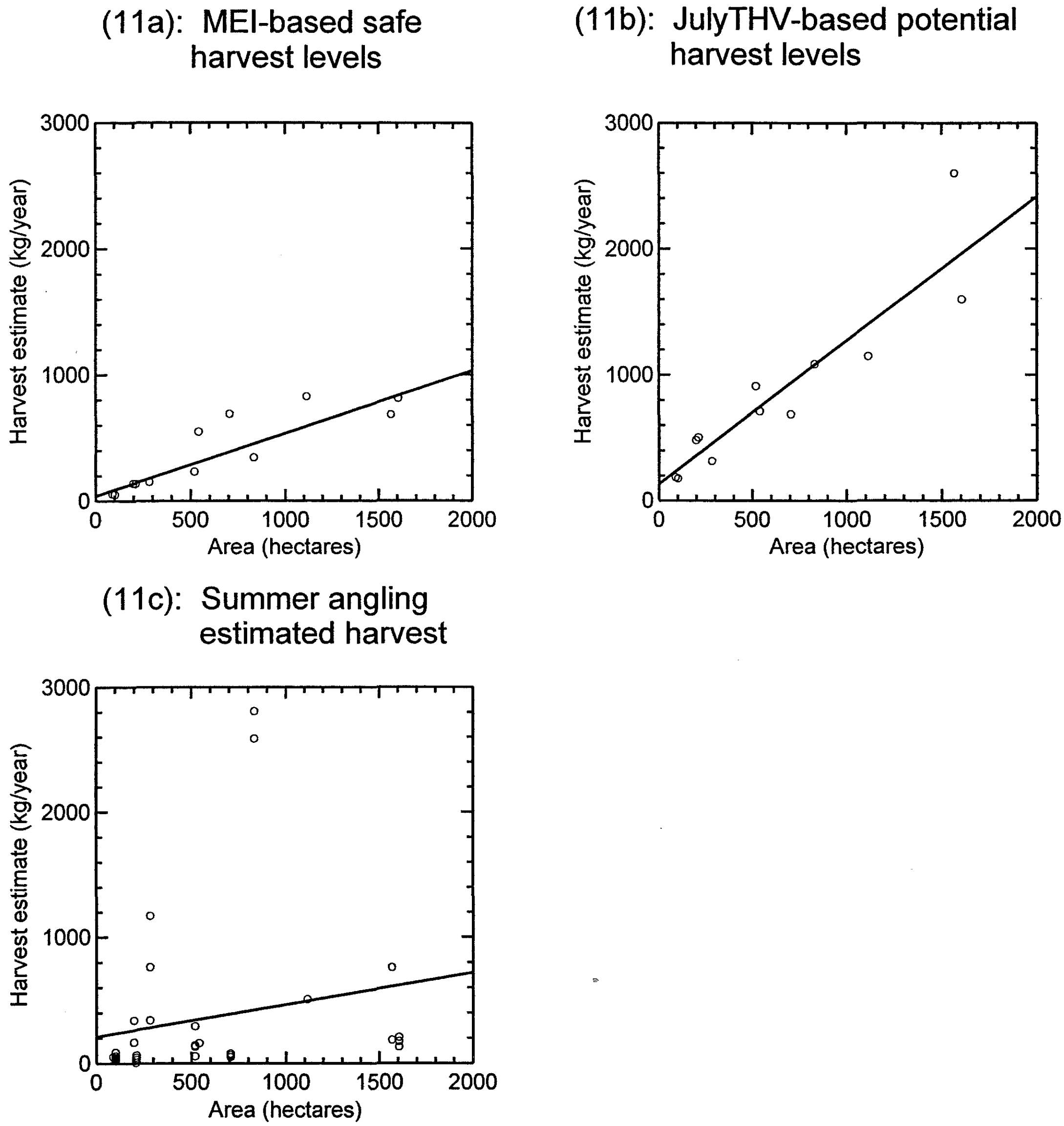

Figure 11 a, b, c. MEI-based and THV-based estimates of potential lake trout harvest and estimated summer angler harvest of lake trout from Minnesota lake trout lakes. Summer creel survey dates range from 1936-1997.

lakes such as these in the face of man-induced stresses.

The seasonal oxygen depletion observed in West Bearskin Lake and the virtual disappearance of oxygen in the metalimnion and hypolimnion in Birch Lake may be related to long term increases in nutrients from cottage, home, or resort development. The lesser development on Mayhew Lake may be reflected in the lesser rate of oxygen depletion of this lake compared to the other two lakes. Unfortunately, we do not have detailed historical data sets to thoroughly document change (i.e., decline) in lake trout habitat quality and quantity. Other lake trout lakes (e.g., East Bearskin, Poplar, Flour, and Greenwood lakes among others) have partially documented oxygen depletion problems that begin at differing times during the thermally stratified period and may vary from year to year. These problems may also be related to cultural eutrophication. Changes in trophic status (i.e., increased production in the epilimnion and metalimnion, followed by decomposition and oxidation) may reduce lake trout habitat quantity and quality, and therefore adversely affect lake trout behavior, feeding, growth and reproduction. Population decline or loss of reproductive success in some lakes may be because of loss of spawning and nursery areas due to substrate degradation (Evans et al. 1990). Habitat degradation on developed or developing lakes will become an increasing occurrence as pressure from developers, local government, and individuals continues, especially if guidelines designed to minimize impacts to lakes are not stringently adhered to and enforced. The combination of cultural eutrophication and over harvest by anglers could cause reproductive failure and the collapse of a fishery, perhaps requiring frequent stocking to maintain a viable fishery. Habitat degradation may also be the cause of the loss of lake trout populations.

THV, as defined by Payne et al. (1990), integrates temperature and oxygen profiles into a single measure. Some lakes with oxygenated but cold hypolimnions had low optimal THV. Although the cold would reduce growth and translate into reduced potential yields, the nature of the stress to lake trout would be quite different from a lake with suboptimum or inadequate hypolimnetic oxygen. Extending the THV measurement to include the maximum depth at which dissolved oxygen is greater than or equal to 6.0 mg/l also seems to be a useful measure of lake trout habitat quantity and quality. The bounds of suitable thermal-oxygen habitat could be redefined as the water depth having temperature $\leq 12\,°C$ with at least 6.0 mg/l dissolved oxygen. These criteria would typically emphasize temperature at the upper boundary of lake trout habitat and oxygen at the lower boundary. This definition would provide a greater contrast between lakes having orthograde oxygen curves and those having clinograde curves. Calculating suitable thermal-oxygen habitat volume (TO_2HV) for lake trout on this basis may allow a more thorough comparison of lakes. A new TO_2HV lake trout harvest model, however, cannot be fully developed for Minnesota's lake trout lakes without actual sustained yield data from the full size range of these lakes.

The THV-based model for estimating potential lake trout harvest (Payne et al. 1990) is useful, but it may not apply to all Minnesota lake trout lakes, especially small lakes. Observations of lake trout use of relatively warm (19-20 °C), epilimnetic waters in three relatively small (16 to 114 ha) Ontario lakes and other reports of lake trout in warm water (Olson et al. 1988; Snucins and Gunn 1995; and previous investigators) prompted Sellers et al. (1998) to suggest that critical habitat for lake trout, particularly in small lakes, is not adequately described by previously assumed niche boundaries. They stated that temperature-based niche boundaries for lake trout (8 °to 12 °C) are too low and too narrow for small lakes with simple fish assemblages and that lake trout niche includes epilimnetic resources, as well as, suitable temperature and dissolved oxygen. In their study, lake trout occupied waters where temperature was greater and less than the fundamental thermal niche ($10\pm2\,°C$) described by Magnuson et al. (1979, 1990). In this study, the presence of lake trout in some small Minnesota lakes theoretically having no optimal $JulyTHV_6$ (e.g. Gordon, Snipe, and Cash lakes) or a very small relative THV_6 (Jim Lake) may indicate that the assumed 12°C upper temperature bound may indeed be too low. Relatively high dissolved oxygen may be more important than temperature alone in determining the presence of lake in small lakes (Evans et al. 1991). According to Sellers et al. (1998), 5 or 6 mg/l dissolved oxygen would be a realistic lower bound for optimal lake trout habitat. They, however, did not specify an upper temperature bound, indicating that lake trout use of epilimnetic waters may be more dependent on potential forage in that zone and the presence or absence of potential competitors or warm- and cool-water predators (e.g., northern pike) than on temperature in some Ontario lakes. Small lakes having few or no competing or predacious warm- or cool-water fishes may allow lake trout to occupy a wider range of thermal habitats than in larger lakes having more diverse fish communities. Thus, for example, THV might be calculated using an upper bound of 15°C for a lake having lake trout and northern pike, while 20°C might be used as the upper bound for a lake trout lake having no potential predators or competitors (B. Parker, personal communication, 2000), instead of 12°C.

MEI yield estimates and July THV yield estimates can be regarded as first and second generation efforts at predicting lake trout yields from minimal data, that are easy to obtain and relatively easy to calculate (Payne et al. (1990). These estimates may allow initial decisions regarding harvest levels for lake trout lakes sustained by natural reproduction. Forty-nine percent of Minnesota's lake trout waters are less than 100 hectares. Only one Ontario lake in the data set used to develop the original JulyTHV model was smaller than 100 hectares in total area (Payne et al. 1990). Therefore, potential yields from the JulyTHV model for Minnesota's smaller lakes should be used cautiously because many are extrapolations beyond the original data set.

The mean of JulyTHV yields (1.51 $kg \cdot ha^{-1} \cdot year^{-1}$) is approximately 3 times the average MEI lake trout yield (0.53 $kg \cdot ha^{-1} \cdot year^{-1}$). This may suggest that adopting the MEI yield for lake trout would be the more conservative approach to selecting harvest and yield for many Minnesota lake trout lakes. The THV approach to estimating yield, however, accounts for habitat quality and quantity, factors that influence yield of individual lakes. Using the THV approach to predicting lake trout yield for individual lakes may allow for cautious tailoring of angling regulations to groups of similar lake types.

MEI and THV lake trout harvest levels, derived from the yield estimates, may not protect lake trout populations in all lakes because other biotic and abiotic variables may be limiting in some lakes. Although sustainable lake trout yields from small lakes, having few competitors and less complex trophic structure, may be greater than yields from larger lakes, having more competitors or predators and more complex trophic structure (Carl et al. 1990), habitat elements other than temperature and oxygen may limit lake trout populations in small lakes. Shallow mixing due to short fetch may limit oxygenation of the hypolimnion and cleansing of potential spawning areas (Payne et al. 1990). This condition may be worsened for small lakes that lie among hills or ridges, having infrequent wind exposure and incomplete spring or fall mixing. Lake trout lakes having these characteristics may have smaller sustainable yields and may be extremely vulnerable to overharvest.

Recent analyses by Ontario biologists (Shuter et al. 1998) indicate that small lakes with low TDS values (e.g., 15 mg/l) are more sensitive to angler exploitation than larger lakes with relatively high TDS values (e.g., 180 mg/l). Low TDS values are characteristic of many Minnesota lake trout lakes (mean=37 mg/l, *N*=69). Thus, lake trout populations in some of Minnesota's small, low TDS lakes may be in jeopardy, and these vulnerable lakes may require more habitat protection and more protection from angler overexploitation (Shuter et al.1998).

Predicted lake trout yields vary within and among lakes, and the variation is attributed to differences in biotic and abiotic factors. Yield variation within lakes having complex basins may be due in part to variation in habitat quality and quantity in different parts of the lake. Year-to-year variation in weather influences thermal budgets. Lake mixing and reoxygenation of the hypolimnion, depth of thermal stratification, primary productivity, and rate of oxygen depletion in the hypolimnion of most lakes and metalimnion of lakes that are oxygen-limited influence optimal habitat volume for lake trout. The differences in potential THV lake trout yield and safe MEI lake trout yield indicate that additional abiotic and biotic variables may need to be accounted for before more precise estimates of sustainable lake trout yield and harvest levels can be made for Minnesota lakes. Some of the biotic variables needed from representative lake trout lakes include: lake trout growth and mortality rates, primary productivity, and for some lakes, a more complete knowledge of differences in lake trophic and community structure as well as angling effort and harvest data. Quantity and quality of spawning habitat is a very important abiotic factor that could limit reproductive success.

From 18 summer and 42 winter creel surveys, Cook and Younk (1998) found that anglers keep a high proportion of lake trout. On average, 15% (SE=3.8) of the lake trout caught in summer are released, while in winter an average of 37% (SE=4.0) of lake trout are released. Not surprisingly, they found greater harvest rates (0.082 fish/angler-hour) for anglers targeting lake trout than for anglers that did not specifically target lake trout (0.034 fish/angler-hour). They found that the average size of lake trout caught by summer and winter anglers was similar, approximately 425 mm (TL) and 0.93 kg. Summer anglers began to harvest (i.e., keep) lake trout at age 3, while winter anglers began keeping lake trout at age 5. They noted that as angling pressure (angler-hours/ha) increased the average size of lake trout decreased. As fishing pressure increases anglers catch rates (fish/hour) decline, and the proportion of smaller fish increases (Cook and Younk 1998).

Human-induced stresses, including overexploitation, introduction of non-native species (e.g., smallmouth bass *Micropterus dolomieu,* walleye, and other species), and cultural eutrophication may have already put some lake trout populations in jeopardy. Some of the lakes in the Superior National Forest and BWCAW may have been stressed due to fishing before the advent of snowmobiles when float- or ski-equipped aircraft could access lake trout lakes. Use of snowmobiles almost certainly increased stress on some sensitive lake trout populations, especially those in relatively small lakes. Aerial counts showed anglers using snowmobiles visited 27 lakes of a sub-sample of 36 lake trout lakes in the BWCAW and Superior National Forest during the winter 1965 angling season (Schumacher et al. 1966).

Restrictions on snowmobile use in the BWCAW may have allowed some stressed lake trout populations to recover or partially recover. With the passage of the Wilderness Act of 1964, legal snowmobile use was limited to certain routes that allowed relatively easy access to some of the larger lake trout lakes, such as Knife, Little Knife, Cypress, Ima, Thomas, and Fraser (Heywood 1981). At that time winter access to smaller lake trout lakes in the BWCAW was restricted to nonmotorized travel (walk, ski, dogsled). Based on aerial counts in winter 1965, Schumacher et al. (1966) indicated that 5 of 36 lakes in Cook County (Trout, Clearwater, Partridge, Dunn, and Fay lakes) in or near the BWCAW boundary may have received yearly angling pressure approaching or exceeding a critical level of approximately 12 angler-hours/hectare. This was considered to be the maximum allowable pressure for a sustainable lake trout yield. That study, however, did not estimate lake trout yield. In 1980, after the 1979 closure of the snowmobile route to Thomas, Ima, and Fraser lakes (Public Law 95-495), fishing pressure (range: zero to 8.9 angler-hours/hectare; $\bar{x}$ = 2.4) on 28 lakes in the MNDNR Ely management area, such as Knife, Little Knife, and Cypress, appeared to increase while it decreased or was eliminated on less accessible lakes (Heywood 1981). In winter 1981, estimated lake trout yield from these 28 Ely Area lakes ranged from 0.0 to 1.1 kg/ha ($\bar{x}$ = 0.35). During winters of 1980-1982, angling pressure on 9 BWCAW lakes in the MNDNR Grand Marais area ranged from 0.0 to 17.2 angler-hours/ha ($\bar{x}$ = 4.3) with pressure being highest on the more accessible lakes. Estimated winter yields on these 9 lakes ranged from 0.01 to 2.14 kg/ha ($\bar{x}$ = 0.57). During the same period, angling pressure on 12 lakes outside or partially outside the BWCAW ranged from <0.1 to 60.4 angler-hours/ha ($\bar{x}$ = 11.8) with pressure being higher on relatively small, stocked lakes. Estimated yields on these 12 lakes in winter ranged from 0.01 to 3.74 kg/ha ($\bar{x}$ = 1.03). Considering Healey's (1978) estimate that lake trout lakes with angling yields exceeding 0.45 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$ likely are overfished, Martin and Olver's (1980) recommendation that yields in the range of 0.25 - 0.75 $kg{\cdot}ha^{-1}{\cdot}year^{-1}$ may be sustainable, and the OMNR (1982) recommendation that a safe lake trout yield may be 25% of the MEI fish yield, some of Minnesota's relatively old, winter creel survey information indicates that sustainable lake trout yield levels were exceeded in some BWCAW lakes and non-BWCAW lakes. This is particularly disturbing because the undetermined harvest from the open-water season may have been a major part of the total annual harvest.

In 1984, the cessation of all legal snowmobile travel within the BWCAW made monitoring winter angling activity in the BWCAW difficult. Almost no quantitative or qualitative angling effort or harvest information has been collected for lakes in the BWCAW since. The closure of snowmobile routes in the BWCAW may have concentrated winter angling effort on lake trout lakes outside and on the periphery of the BWCAW. For almost all lake trout lakes in the BWCAW we do not know how current winter and summer harvests relate to either MEI or THV harvest levels. Yet, angling for lake trout, especially in the spring before thermal stratification, is a popular activity in and out of the BWCAW. Some of the native lake trout fisheries likely have been or are being overexploited by a combination of summer and winter angling. Since the snowmobile access to most lakes is illegal, it is likely that most harvest of lake trout in the BWCAW now occurs during the open-water season, except perhaps for BWCAW lake trout lakes that are easily accessed during winter (e.g., Partridge, Daniels, and Duncan lakes). There are, however, some BWCAW lakes that are targeted by winter anglers that traveling by snowshoes, skis, or dogsled. It is possible that groups of anglers, summer or winter, could exceed the safe harvest levels for some small lakes.

Management and Research Implications

Given that lake trout are highly sought-after and are a limited resource in Minnesota, lake trout populations that may be stressed should be identified. They should be considered for greater protection from over-exploitation by anglers, and greater protection from cultural eutrophication or other human-induced stresses. It is likely that there are few, if any, Minnesota lake trout populations capable of supporting commercial fisheries. Angler harvest levels higher than those occurring now may not be sustainable for most unstocked lake trout lakes and some lakes are probably already over-harvested. There is a continuing need to determine the status and use of Minnesota's relatively remote, unstocked lake trout populations, as well as those in more accessible lakes.

Lake trout populations that may be at risk should be identified by further evaluation of thermal habitat (Ryan and Marshall 1994). Their definition of lake trout niche, based on mean depth, primary productivity, and seasonal oxygen depletion, can be used tentatively to identify and categorize Minnesota's lake trout populations that may be at risk. Further analyses of existing and new data, using concepts and procedures developed and discussed by Payne et al. (1990), Ryan and Marshall (1994), Marshall (1996), and Shuter et al. (1998) are recommended. Greater understanding of lake trout use of relatively warm water in some lakes (Sellers et al. 1998) may require modification of the lake trout niche definition. Further evaluation of lake trout behavior, lake trout predator-prey relationships, growth, and angler exploitation would be useful in making lake trout management decisions.

Additional field data is needed. TDS measurements can easily be made with inexpensive, highly portable meters. Detailed depth-temperature-dissolved oxygen profiles should continue to be gathered from known and suspected lake trout lakes, especially during the July-August stratification. On specific lakes, where dissolved oxygen is suspected to be limiting, it would be useful to have DTO_2 data collections before stratification to determine the extent of oxygen recharge in spring, and just before fall mixing to have a more complete understanding of oxygen depletion. DTO_2 data from multiple years would be valuable in assessing year-to-year variation in lake trout habitat quantity and quality. Field crews should collect DTO_2 data from the deepest location on a lake as standard procedure. For lakes with complex or separate basins, multiple DTO_2 profiles are useful in documenting within lake variation. Additional water transparency (summer Secchi disc visibility), spring total phosphorus, and summer chlorophyll *a* concentration measurements are needed.

With few exceptions, there is little current, reliable harvest or yield information from Minnesota lake trout lakes to compare to safe or potential harvest estimates. A great deal of effort would be required to obtain the needed data. Yield estimates for an entire angling year are rare. Carefully designed creel surveys and population studies can produce valuable fishery and population statistics, however, these efforts are labor intensive and difficult in remote areas. Angler diaries or surveys may be tested. Current status of lake trout in remote lakes can be verified by careful sampling with alternative netting gear designed to minimize mortality, especially on small lakes, and acoustic methods may be tested. Radio or ultrasonic telemetry may provide better understanding of lake trout habitat use.

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Appendix Table 1. Dates of winter (W) and summer (S) (i.e., spring-summer-fall) creel surveys of Minnesota lake trout lakes for which yield and harvest estimates are included in this report (see Table 4). Abbreviations: BWCAW = Boundary Waters Canoe Area Wilderness; Y = yes; N = no.

Lake name	MN lake number	BWCAW lake (Y/N)	Lake trout stocked (Y/N)	Season	Creel survey year(s)	Reference
Roosevelt	11-0043	N	Y	W	1995	Bohlander, D.J. 1996
Trout	16-0049	N	N	S	1979-1983, 1997	various
				W	1978-1981, 1984	various
Greenwood	16-0077	N	Y/N	W	1982	Persons, S.E. 1985a
Pike, West	16-0086	Y	N	S	1954, 1955, 1956	Micklus, R.C. 1959a
Mountain	16-0093	Y	N	S	1954, 1955, 1956	Micklus, R.C. 1959b
Alder	16-0114	Y	N	W	1982	Persons, S.E. 1985a
Clearwater	16-0139	Y	Y/N	S	1936, 1954, 1955, 1956,	Micklus, R.C. 1959c,
				S	1986, 1997	Persons, S.E. 1987, 1998
				W	1981, 1985	Persons, S.E. 1985, 1986
Daniels	16-0150	Y	Y/N	W	1980, 1981, 1984, 1985, 1991	Persons, S.E. 1985a, 1986, 1992
Trout, Little	16-0170	Y	N	W	1980, 1981	Persons, S.E. 1985a
Ram	16-0174	Y	Y	W	1980, 1981	Persons, S.E. 1985a
Kemo	16-0188	N	Y	W	1981, 1984	Persons, S.E. 1985a, 1989
Bearskin, W.	16-0228	N	Y	S	1986, 1997	Persons, S.E. 1987, 1998
				W	1980, 1981,	Persons, S.E. 1985a
				W	1983-1990	Siesennop, G.D. 1992
Duncan	16-0232	Y	Y	S	1986	Persons, S.E. 1987
				W	1980, 1981	Persons, S.E. 1985a
				W	1983-1990	Siesennop, G.D. 1992
Partridge	16-0233	Y	N	W	1980, 1981	Persons, S.E. 1985a
Moss	16-0234	N	Y	W	1980, 1981, 1985	Persons, S.E. 1985a, 1986
South	16-0244	Y	N	W	1973, 1974, 1975, 1980, 1981	Kucera, T.A., and B.L. Torp. 1976a,b; Torp, B. et al. 1977, Persons, S.E. 1985a
Birch	16-0247	N	Y	S	1986	Persons, S.E. 1987
				W	1973, 1974, 1975, 1980, 1981	Kucera, T.A., and B.L. Torp. 1976a,b; Torp, B. et al. 1977; Persons, S.E. 1985a
				W	1983-1990	Siesennop, G.D. 1992
North	16-0331	N	N	S	1992	Persons, S.E. 1993
Mayhew	16-0337	N	Y	S	1986	Persons, S.E. 1987
				W	1973, 1974, 1975, 1980, 1982	Kucera, T.A., and B.L. Torp. 1976a,b; Torp, B. et al. 1977; Persons, S.E. 1985
				W	1983-1990	Siesennop, G.D. 1992
Gunflint	16-0356	N	Y/N	S	1983, 1992	Persons, S.E. 1984, 1993
				W	1980, 1982, 1984, 1990, 1993	Persons, S.E. 1984, 1991; Eiler, P.D. 1993
Loon	16-0448	N	Y/N	S	1986	Persons, S.E. 1987
				W	1980, 1984, 1990, 1993	Persons, S.E. 1984, 1985a, 1991; Eiler, P.D. 1994
Tuscarora	16-0623	Y	N	W	1973, 1974, 1975, 1980, 1981	Kucera, T.A., and B.L. Torp. 1976a,b; Torp, B. et al. 1977, Persons, S.E. 1985a

Appendix Table 1. Continued.

Lake name	MN lake number	BWCAW lake (Y/N)	Lake trout stocked (Y/N)	Season	Creel survey year(s)	Reference
Seagull	16-0629	Y	N	S	1937, 1956, 1957	Micklus, R.C. 1959d
				W	1980	Persons, S.E. 1985a
Saganaga	16-0633	Y	N	S	1984, 1985, 1991, 1995	Persons, S.E. 1985b, 1986, 1992, 1996
				W	1988, 1992, 1996	Persons, S.E. 1989, 1993, 1997
Trout, Big	18-0315	N	Y	S	1988	Nelson, R.T. 1989
				W	1995	Bohlander, D.J. 1996
Trout	31-0410	N	Y	S	1982-1984	Thompson, R., and D. Holmbeck, 1985
				W	1982	Holmbeck, D. 1982
Caribou	31-0620	N	Y	W	1979-1982	Holmbeck, D. 1982
Cherry	38-0166	Y	N	W	1980	Heywood, C.M. 1981
Topaz	38-0172	Y	N	W	1980	Heywood, C.M. 1981
Holt	38-0178	Y	N	W	1980	Heywood, C.M. 1981
Hanson	38-0206	Y	N	W	1980	Heywood, C.M. 1981
Ester	38-0207	Y	N	W	1980	Heywood, C.M. 1981
Cypress	38-0211	Y	N	W	1980	Heywood, C.M. 1981
Rabbit	38-0214	Y	N	W	1980	Heywood, C.M. 1981
Kekekabic	38-0226	Y	N	W	1980	Heywood, C.M. 1981
Amoeber	38-0227	Y	N	W	1980	Heywood, C.M. 1981
Knife, Little	38-0229	Y	N	W	1980	Heywood, C.M. 1981
Missionary	38-0398	Y	N	W	1980	Heywood, C.M. 1981
Explorer	38-0399	Y	N	W	1980	Heywood, C.M. 1981
Knife	38-0404	Y	N	W	1980	Heywood, C.M. 1981
Snowbank	38-0529	Y/N	N	W	1973, 1974, 1975, 1984, 1991	Torp, B. et al. 1977; Kucera, T.A., and B.L. Torp 1976a,b; Heywood, C.M. 1986; Thompson, D. 1991
Ojibway	38-0640	N	N	W	1973, 1974, 1975, 1984	Torp, B. et al. 1977, Kucera, T.A., and B.L. Torp 1976a,b; Heywood, C.M. 1986
Grindstone	58-0123	N	Y	S	1962, 1963, 1966, 1985	Groebner, J. 1969; Korby, B., and R. Mead, 1986
Burntside	69-0118	N	Y	W	1973, 1974, 1975, 1984, 1992	Torp, B. et al. 1977; Kucera, T.A., and B.L. Torp 1976a,b; Heywood, C.M. 1986; Thompson, D. 1992

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