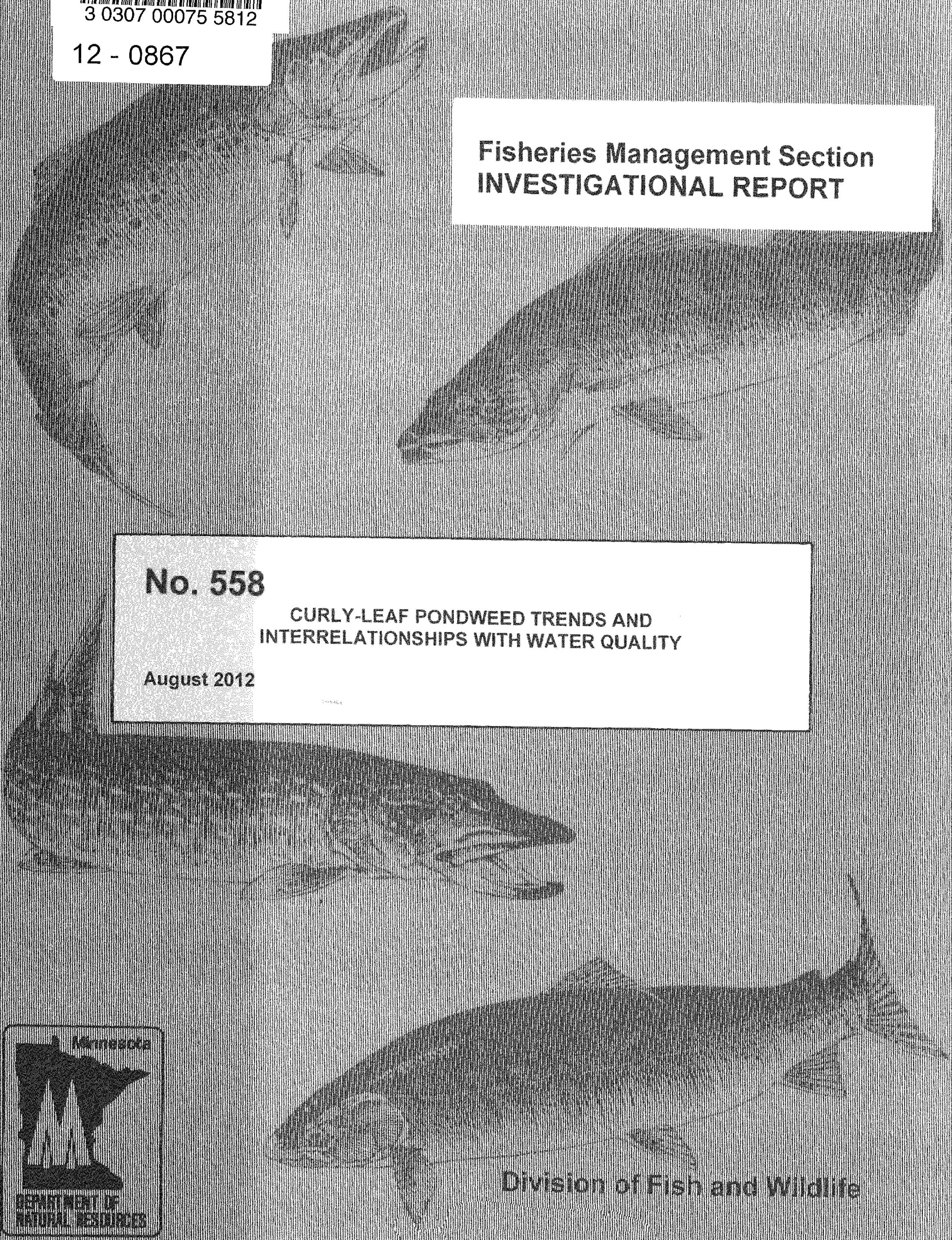

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CURLY-LEAF PONDWEED TRENDS AND INTERRELATIONSHIPS WITH WATER QUALITY[1]

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Abstract.— Curly-leaf pondweed *Potamogeton crispus* is a long-established invasive in Minnesota. It is common throughout southern and central Minnesota and is thought to be expanding northward. Curly-leaf pondweed typically grows abundantly in spring in productive lakes and then senesces in mid-summer followed by algal blooms. Results from the literature and Sentinel Lakes suggest the relationships between curly-leaf senescence and water quality vary substantially among lakes. The post-senescence decreases in water clarity are most pronounced in shallow lakes with minimal native vegetation. In these lakes, abundant growth of curly-leaf is followed by severe algal blooms as described above. However, in shallow lakes with abundant native vegetation, the post-senescence decreases in water clarity are muted. In deep lakes by comparison, we saw fewer decreases in water clarity following curly-leaf senescence. Where curly-leaf density is low to moderate, observations of decreases in water clarity following curly-leaf senescence were minimal. We also share unexpected findings of widespread, short-term declines in curly-leaf pondweed and evaluate possible reasons for these declines. Evidence suggests that high early-season snowfall may decrease curly-leaf pondweed production in lakes even if ice-out occurs earlier. These findings provide a basis for more targeted follow-up investigations that seek to predict what lake environments should be most favorable for curly-leaf pondweed growth and where the plant is most likely to have negative consequences on water quality and fish habitat. This will facilitate better invasive plant management decisions and actions and more efficient targeting of management resources. Finally, our findings also suggest that climate change may significantly affect habitat viability for curly-leaf pondweed. If more winter precipitation falls as snow, this could reduce curly-leaf pondweed abundance across lakes. If more winter precipitation falls as rain, curly-leaf pondweed populations could expand. Current climate models clearly place Minnesota in the transition between winter precipitation that falls as rain or snow, with the line potentially moving north over the long-term as the climate warms.

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Introduction

The purpose of this report is to examine several factors that may contribute to the growth of the non-native invasive aquatic plant curly-leaf pondweed *Potamogeton crispus*, the impact of curly-leaf pondweed on lake water quality and lake ecology, and share recent patterns of curly-leaf pondweed growth based on recent data from 11 sentinel lakes where curly-leaf pondweed is present and monitored (Figure 1). These study lakes are part of a cooperative long-term lake monitoring program administered by the Minnesota Department of Natural Resources (http://www.dnr.state.mn.us/fisheries/slice/index.html). Curly-leaf pondweed occurs in 13 of the 24 sentinel lakes but curly-leaf pondweed frequency was the target of spring vegetation surveys in 2008 – 2010 in only 11 of these lakes. Additional lakes with very low densities or no curly-leaf pondweed are used as a basis for comparison when appropriate.

Curly-leaf pondweed is widespread throughout North America and Canada (Bolduan et al. 1994). In Minnesota, the exact date of introduction is unknown but it is believed to have been present since the early 1900s when common carp *Cyprinus carpio* were brought into the state. As of 2011, curly-leaf pondweed is found in over 730 Minnesota lakes. It is common in central and southern Minnesota with a vast majority of occurrences in the Transition Forest zone (North Central Hardwoods Forest ecoregion) and is expanding northward (Table 1).

Curly-leaf pondweed has a unique life history in that rapid growth from overwintering plants occurs much earlier in spring than most other native macrophyte species (10-15 °C; Bolduan et al. 1994). When water temperatures exceed 11° C in spring, curly-leaf plants develop dormant vegetative propagules called turions (Woolf and Madsen 2003). Turion production rapidly increases when temperatures exceed 25 °C and the plant senesces shortly thereafter (Woolf and Madsen 2003; Chambers et al. 1985). Once water temperature cool below 20 ° C with decreased daylight (typically in mid to late September), turions sprout into an overwintering form morphologically distinct from the spring growth form (Bolduan et al. 1994; Catling and Dobson 1985). Most authors cite that curly-leaf pondweed is tolerant, if not selective of cool climate conditions (Bolduan et al. 1994; Catling and Dobson 1985; Nichols and Shaw 1986). However, little is known about the basal metabolic needs of overwintering curly-

Table 1. Documented number of waterbodies with curly-leaf pondweed in the major Minnesota land types. It is likely that these are large underestimates of the true number of waterbodies since many lakes have not been assessed.

Land Type	No. Documented Waterbodies	Total No. Lakes w/ID Nos.	Minimum occurrence percentage
Canadian Shield	2	1,964	0.1
Northern Wetland	1	520	0.2
Red River Valley	5	774	0.6
Northern Forest	126	6,809	1.9
Transition Forest	525	10,580	5.0
Prairie and Cornbelt	57	4,525	1.3
Driftless Area	2	130	1.5

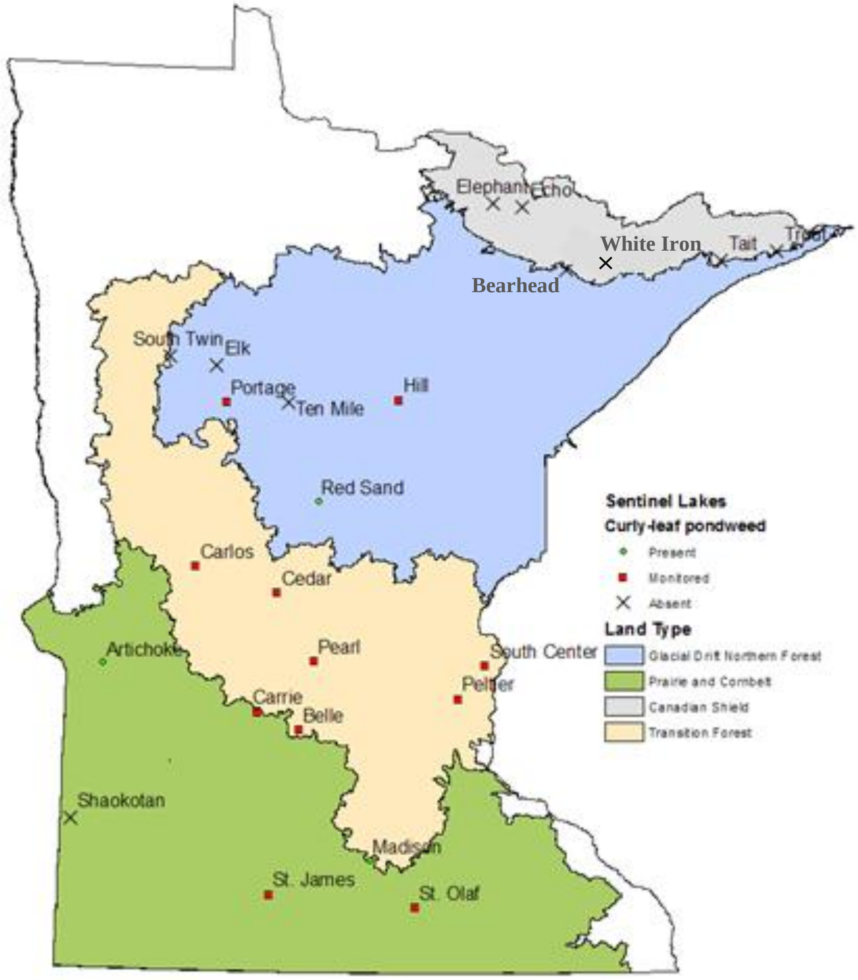


Figure 1. Map of curly-leaf pondweed (CLP) status in the 24 sentinel lakes and major land types. Lakes that are designated as "monitored" have CLP and have been monitored annually from 2008 through 2010. Lakes designated as "Present" have CLP but have not been monitored.

leaf plants and their ability to survive long periods under snow-covered ice. Wu et al. (2009) documented reduced viability of sprouted turions with anoxic sediment conditions and light at 1% of natural light conditions. Assuming many northern lakes have been exposed to curly-leaf pondweed at some point over the last 100 years, the lack of occurrence in northern Minnesota lakes suggest ice and snow cover may limit their distribution across Minnesota (Figure 2).

Lake productivity also influences curly-leaf pondweed abundance. Although it can be found in a wide-range of environmental conditions, curly-leaf pondweed appears most common and abundant in alkaline (> 100 mg/L calcium carbonate alkalinity, $CaCO_3$), phosphorus-rich lakes (TP between 50 – 100 µg/L; Bolduan et al. 1994). These conditions are most common in the transition and prairie land types in Minnesota (Heiskary and Wilson 2005). Growth appears most rapid and extreme in warm, eutrophic lakes where large summer die-offs are often followed by algae blooms due presumably, in part, to the release of nutrients from decaying plants (Nichols and Shaw 1986, Bolduan et al. 1994, James et al. 2002).

Other factors may contribute to algal blooms that follow curly-leaf senescence. For example:

1. Senescence may result in the accumulation of dead plant material on the surface of the sediment leading to development of anoxic conditions, which accelerates sediment P release (Welling 2010).
2. The lack of plants in the water column may allow an increase in mixing because of wind or benthivorous fish (i.e., bioturbation), which may increase P availability to phytoplankton and promote algal blooms (Weber and Brown 2009; Jackson et al. 2010).
3. As curly-leaf pondweed disappears, zooplankton may lose an important refuge and may be much more susceptible to fish predation (Schriver et al. 1995).
4. Watershed P loading from mid-summer events.

In mesotrophic, northern Minnesota lakes, curly-leaf pondweed turion production is likely delayed by cooler water temperatures, and growth and subsequent diebacks are less pronounced. However, information that describes limnological conditions affecting curly-leaf pondweed growth has largely been anecdotal to date. Likewise, there has been minimal quantitative data that demonstrate the ecosystem-wide effects of excessive curly-leaf growth and senescence (e.g., significant internal phosphorus loading).

Despite anecdotal evidence in eutrophic lakes of reduced water quality in summer following senescence of curly-leaf pondweed, there is little evidence from experimental whole-lake treatments that suggests removing curly-leaf pondweed from these systems improves water quality (Welling 2010). In fact, removing large areas of curly-leaf pondweed (or any other plant for that matter) without replacement of voided areas with other aquatic plant species may lead to more degradation of water quality and fish habitat than leaving the infestation unmanaged (Valley et al. 2004; Kovalenko et al. 2010). In the absence of native macrophytes, curly-leaf pondweed provides habitat for vegetation-dependent native game fish such as northern pike (*Esox lucius*), largemouth bass (*Micropterus salmoides*), and bluegill (*Lepomis macrochirus*) (Valley et al. 2004; R. Valley unpublished data). In fact, because of shading from high phytoplankton density and suspended sediment caused by runoff from municipal and agricultural sources, most southern Minnesota lakes do not support sufficient native aquatic plant growth. Often, curly-leaf pondweed is the only aquatic plant that grows in sufficient abundance in these systems to support northern pike, largemouth bass, and bluegill populations. Management efforts that remove curly-leaf pondweed without restoring native macrophyte cover likely lead to significant reductions of these managed fish populations (R. Valley unpublished data).

Lake Morphometric and Watershed Characteristics.

Lake basin morphometry and watershed characteristics have strong influences on lake water quality and can play a role in the relative density and distribution of rooted vegetation. The sentinel lakes display a wide range of lake and watershed conditions that can affect

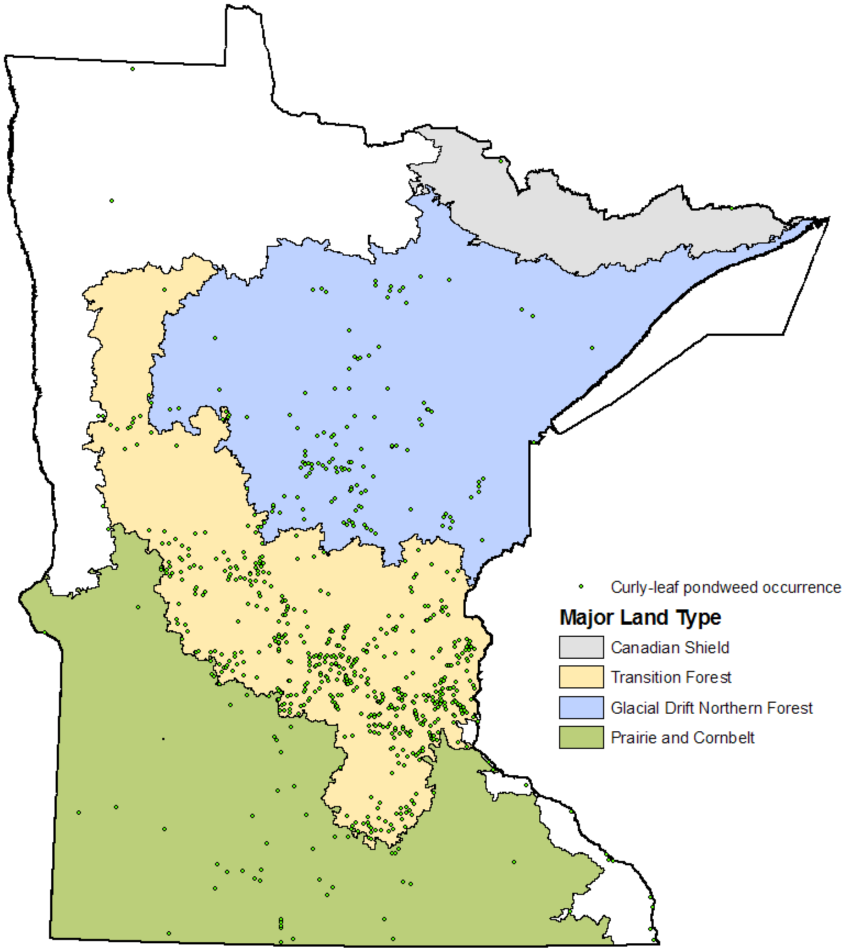


Figure 2. Distribution of curly-leaf pondweed in water bodies across the major land types of Minnesota.

curly-leaf pondweed growth (Table 2 and 3). Although curly-leaf pondweed can be found in sentinel lakes that range greatly in total phosphorus (TP) concentrations, curly-leaf pondweed has a strong tendency to occur in watersheds dominated by urban or agricultural landuse in the southern half of the state. These landuses often are associated with high nutrient runoff and riparian vegetation alteration. In-lake disturbances such as destruction of aquatic plants by shoreline residents and motorized recreation may further reduce rooted vegetation. The general nature of invasive species is to exploit habitats where suitability for extant native species has been altered in favor of conditions now more suitable for the introduced species (Moyle and Light 1996).

Climate Summary. Given that curly-leaf pondweed life history is strongly dependent on light and temperature in winter, spring, and summer, climatic gradients across Minnesota may limit habitat suitability for the plant. Indeed, despite being present in the State for over a century, curly-leaf pondweed is much more common in the southern half of the State where winter ice cover is shorter and spring and summer water temperatures are warmer (Figure 3). However, lake fertility and human disturbance is also lower as one travels northward in the state and may also contribute to lower curly-leaf habitat suitability. Still, although establishing actual dates of introduction is difficult, over the past decade, increasingly more infestations are being detected in the northern part of the state. An assumption must be made that new detections actually indicate recent introductions rather than increased awareness. Due to spotty historical data collection, this assumption is difficult to verify. Still, recent spread into northern lakes (Climate Division 2) is plausible since most winters have been warmer and drier from a period of 1980 – 2006 (National Climatic Data Center; Southern Climate Impacts Planning program; http://www.southernclimate.org/products/trends.php).

Methods

Curly-leaf pondweed surveys. ―Annual surveys specifically targeting curly-leaf pondweed have been completed in 11 of the 13 sentinel lakes with curly-leaf pondweed since 2008 (Figure 1). Surveys were conducted during periods of peak curly-leaf pondweed growth, typically during the month of May or June of each year. Later in July or August, surveys targeting all plant species were repeated in all sentinel lakes except Ten Mile Lake. Frequency of occurrence of plants was assessed using the point-intercept method (Madsen 1999). This method entailed visiting sampling points on a grid within the vegetated zone of the lake, throwing a two-sided rake over one side of the boat at each point, raking the bottom approximately 1 m, then retrieving the rake and identifying all species present, and recording the depth. Survey points were spaced approximately 80-m (0.7 points per littoral acre) and covered all potential areas of vegetation growth in each lake equally. Consequently, patterns in percent frequency should correspond with patterns in percent cover. Because the depth of plant growth varies widely across lakes and can often change from year to year depending on water clarity conditions, we chose a standard depth of 15 ft over which to compute and compare frequency statistics.

In addition to mapping surface growth, indicator kriging (Isaaks and Srivastava 1989; Valley et al. 2010) was used with point-intercept survey data on Pearl Lake to estimate the areal coverage of curly-leaf pondweed in 2008 – 2010. Grid cell predictions that were $\geq$ 50% probability of occurrence were classified as present and summed across the total area of the basin. This technique and threshold appears to produce relatively accurate maps of areal cover of macrophytes (R.D. Valley, Unpublished data).

Water Quality. ―Water samples were collected monthly from May through September over a minimum of two summers for all lakes in this study during a period from 2008-2010. Following two complete summers of data collection, seasonal collections were instituted for

Table 2. Lake and watershed morphometric characteristics of sentinel lakes where curly-leaf pondweed occurs.

Lake	DNR Lake ID	Lake Basin (ha)	Max. Depth (m)	% Veg. Freq. Depth ≤ 4.6m	Watershed Size (ha)	Depth of Veg growth (m)	Mean TP[1] (µg/L)	Chl a[1] (µg/L)	Secchi (m)[1]
Cedar	49-0140-00	96	26.8	95	649	5.0	13	3	4.0
Carlos	21-0057-00	1,055	48.7	86	63,361	4.9	16	4	3.2
Carrie	34-0032-00	36	7.9	30	1,636	0.9	22	7	1.1
Hill (main)	01-0142-01	265	14.6	92	3,709	3.9	22	6	4.2
Hill (SW)	01-0142-02	50	7.3	61	10,412	3.1	36	11	3.0
St. Olaf	81-0003-00	37	9.1	33	112	1.3	37	20	1.5
Pearl	73-0037-00	305	5.5	76	6,601	3.6	40	16	1.9
South Center	13-0027-00	336	30.5	66	4,366	2.2	51	43	1.2
St. James	83-0043-00	83	4.9	79	946	2.7	52	22	1.3
Belle	47-0049-01	375	6.7	11	2,107	1.7	55	20	1.1
Portage	29-0250-00	174	4.6	77	1,212	3.8	56	24	1.1
Madison	07-0044-00	580	1.9	28	4,519	3.8	78	44	1.0
Artichoke	06-0002-00	795	4.0	3	8,576	2.0	248	24	0.8
Peltier	02-0004-00	223	4.9	58	27,937	1.7	266	107	0.8

[1]Average summer (1-June – 30 Sep.) epilimnetic total phosphorus, Chl-a, and Secchi based on data from 2000-2009.

Table 3. Watershed land cover and landuse area based on NLCD-2001 land use data and classifications. Lakes with curly-leaf present are shaded in gray. Data are sorted by disturbance level.

			Disturbed (ha)			Undisturbed (ha)			%
Lake	Landtype	Total	Ag	Urban	Mining	Forest	Water	Grass	Disturbed
Trout	Shield	188	0	0	0	143	45	0	0
Bearhead	Shield	446	0	1	0	318	127	0	0.2
Tait	Shield	443	0	0	0	371	72	0	0
Elephant	Shield	724	1	2	0	538	177	5	0.4
Elk	Forest	1,435	2	7	0	1235	190	1	0.6
Echo	Shield	5,252	11	40	1	4358	783	59	1.0
White Iron	Shield	97,590	69	517	474	81,405	14,896	228	1.1
S. Twin	Forest	1,104	4	16	0	813	260	11	1.8
Ten Mile	Forest	4,178	71	82	2	2,915	1,079	29	3.7
Hill	Forest	4,215	340	137	2	3,151	357	230	11.4
Red Sand	Forest	746	28	72	0	354	274	17	13.4
Portage	Forest	491	83	18	1	303	74	12	20.8
Cedar	Trans.	262	109	9	0	88	52	3	45.0
Peltier	Trans.	11,307	4,301	1,612	0	1,978	2,958	459	52.3
Carlos	Trans.	25,643	11,864	2,316	6	4,013	5,966	1,477	55.3
Shaokotan	Prairie	1,444	791	62	0	5	201	385	59.1
S. Center	Trans.	1,767	907	143	0	296	400	22	59.4
Artichoke	Prairie	3,471	2,228	159	0	34	982	68	68.8
Pearl	Trans.	2,671	1,735	134	1	391	291	119	70.0
Madison	Prairie	1,828	1,173	129	0	85	427	14	71.2
Carrie	Prairie	662	480	27	0	55	87	12	76.6
St James	Prairie	383	272	48	2	3	58	0	84.1

many of the lakes with samples in spring (April or May), summer (late July or August) and fall (late September or October). Lake surface water and phytoplankton (algae) samples were collected by MPCA staff with an integrated sampler, a poly vinyl chloride (PVC) tube 2 meters (m) in length, with an inside diameter of 3.2 centimeters (cm). Zooplankton samples were collected via vertical net tows. Temperature and dissolved oxygen (DO) profiles and Secchi disk transparency measurements were also taken. Automated temperature sensors were suspended 6 ft below the surface in most sentinel lakes and logged temperature data at 30-min intervals year-round. Most sampling procedures employed are described in MPCA (2006).

Laboratory analysis was performed by the laboratory of the Minnesota Department of Health using United States Environmental Protection Agency-approved methods. Samples were analyzed for nutrients, color, solids, pH, alkalinity, conductivity, chloride, cations, anions and chlorophyll-a (Chl-a). Phytoplankton samples were analyzed at the MPCA using a rapid assessment technique. Zooplankton samples were analyzed by MDNR staff using standard techniques.

Results and Discussion

Surface water temperatures

Surface water temperature provided a direct means for evaluating the impact of temperature on plant growth, water quality, etc. within a given lake. Dataloggers placed in most of the Sentinel lakes were a primary source of data**.** Available data for 2008, 2009, and 2010 are summarized in Table 4. Unfortunately, loggers were not installed in all lakes for all three years and some data was lost as well. Average surface water temperature was quite consistent within lakes among years; however, spring temperatures within lakes increased from 2008-2010 (Table 4).

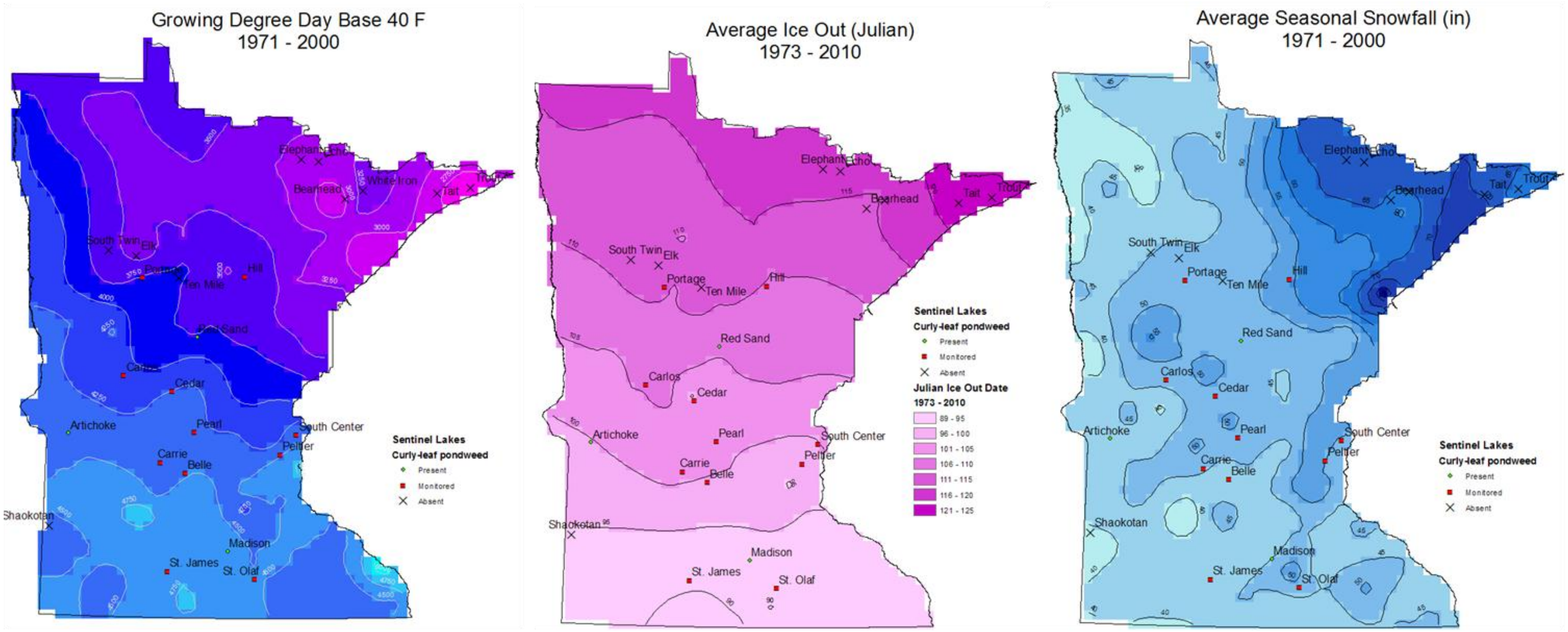


Figure 3. Relevant climatic gradients across Minnesota and occurrence of curly-leaf pondweed in the sentinel lakes.

Table 4. Average daily surface water temperatures based on logger data for 2008, 2009 and 2010. Includes open water mean, spring mean (Temp of all days ≥ 5 °C up to May 31st) and summer mean (June 1st – Sep. 30th) for lakes with available data. Lakes grouped by land type to facilitate comparison.

Land Type	Lake	2008 Mean Temp	2008 Mean spring	2008 Mean sum.	2009 Mean Temp	2009 Mean spring	2009 Mean sum.	2010 Mean Temp	2010 Mean spring	2010 Mean sum.
Shield	Bearhead	15.8	9.7	19.2	15.9	10.5	19.4	15.9	11.9	20.2
	Echo	16.1	11.2	19.3	16.5	11.1	19.3	16.3	12.7	19.7
	Elephant	15.9	9.3	19.6	16.0	10.5	19.4	15.9	11.8	20.1
	Trout	15.4	7.7	18.5	14.9	8.0	18.4	NA	NA	NA
	White Iron	16.3	10.4	19.5	15.7	10.5	19.1	15.8	11.6	20.0
	Mean	**15.9**	**9.7**	**19.2**	**15.8**	**10.1**	**19.1**	**16.0**	**12.0**	**20.0**
Forest	Elk	16.5	8.8	20.5	15.0	9.3	20.1			
	Portage	16.2	9.9	20.6	16.3	11.2	20.5	16.4	11.9	20.9
	Red Sand	17.1	11.2	21.6	16.2	11.0	21.5	17.4	13.1	21.9
	South Twin	16.3	9.3	20.4	15.8	10.3	20.1	16.0	11.4	20.8
	Ten Mile	15.7	7.5	19.2	14.8	8.4	19.3	15.8	10.0	20.4
	Mean	**16.3**	**9.3**	**20.5**	**15.6**	**10.0**	**20.3**	**16.4**	**11.6**	**21.0**
Transition	Belle	17.3	10.6	22.0	15.6	11.3	21.6	17.6	12.8	22.5
	Carlos	16.7	9.0	20.5	NA	NA	NA	NA	NA	NA
	Cedar	17.4	11.0	21.6	16.0	10.9	21.6	17.1	11.9	22.2
	Pearl	16.7	10.1	21.6	15.1	10.6	21.4	17.1	13.3	22.3
	Peltier	18.1	12.7	22.4	16.7	14.0	22.0	NA	NA	NA
	Mean	**17.2**	**10.7**	**21.5**	**15.9**	**11.9**	**21.7**	**17.1**	**12.6**	**22.3**
Prairie	Carrie	NA	11.4	16.9	15.6	11.5	21.7	17.9	13.3	23.0
	Artichoke	NA	NA	21.9	16.1	12.6	21.1	17.2	12.3	22.2
	Madison	NA	NA	NA	16.1	11.8	22.0	18.3	13.5	23.2
	St. James	NA	NA	NA	15.8	13.0	20.9	NA	NA	NA
	St. Olaf	NA	NA	NA	16.7	13.2	22.1	18.5	13.9	23.6
	Mean	**NA**	**NA**	**NA**	**16.0**	**12.2**	**21.6**	**17.9**	**13.2**	**22.9**

The rate and timing of seasonal temperature changes and peak temperatures can influence curly-leaf growth, turion production, and senescence. Datalogger records from three lakes with curly-leaf: St. Olaf (Prairie), Peltier (Transition) and Portage (Forest) and one lake without curly-leaf: Bearhead (Shield) provide some useful insights on this (Figure 4). St. Olaf and Peltier Lakes show a similar progression in temperature from spring through summer 2009. Woolf and Madsen (2003) in research on southern Minnesota lakes found that turions start to form on the plants in these lakes very soon after spring growth is initiated. When water temperatures exceeded 25° C in Peltier and St. Olaf in late June of 2009, turion production rates were probably highest and the plants likely senesced soon thereafter (Chambers et al. 1985). In contrast, Portage Lake warmed at a slower rate (temperatures exceeded 11° C 17 days later than Peltier) and never reached 25° C in 2009 and only periodically reached 25° C in 2010. Similarly, Bearhead Lake, which is much farther north, exceeded 11° C 25 days later than Peltier and never reached 25° C in 2009 and exceeded 25° C only two days in August 2010. Thus, the thermal environment for propagule production (and by extension population growth) may be limiting in northern Minnesota Lakes but not south or central Minnesota lakes (Figure 4).

Patterns in curly-leaf pondweed frequency

Curly-leaf pondweed frequency was greatest in sentinel lakes of intermediate productivity as indicated by summer TP (Figure 5). Based on St. Olaf, Pearl, South Center and St. James, TP ranged from 37-52 µg/L, TKN from 1.1-1.4 mg/L and Chl-a from 16 - 43 µg/L (Table 2). Interestingly, despite having TP similar to South Center, St. James, and Portage lakes, curly-leaf pondweed (as well as other macrophytes) was rare in Belle Lake (Figure 6).

Across the network of sentinel lakes where curly-leaf pondweed was assessed, mean curly-leaf pondweed frequency declined each year with a 37% decline in frequency being observed between 2008 and 2010 across all lakes (Figure 5). Declines were especially pronounced in St. Olaf, St. James, Portage, and Peltier (Figure 5). Given the synchronicity of trends and the geographic spread of surveyed lakes, it is likely that curly-leaf pondweed growth responded primarily to large-scale environmental conditions (as opposed to unique local watershed or in-lake conditions). On aver-average, across the lakes, 2011 was similar to 2009 and 2010 levels, which suggest an approximate equilibrium may have been reached with respect to curly-leaf frequency.

As curly-leaf pondweed frequency declined, increases in summer vegetation frequency of all taxa were observed in some lakes (St. Olaf, St. James, South Center, Portage; Figure 6). However, a modest decline in summer vegetation frequency was observed in Pearl in 2010 (Figure 6). These observations run contrary to the expectation of reduced summer plant cover with high curly-leaf pondweed cover.

Aquatic plant removal by lake associations and homeowners across all infested sentinel lakes did not likely play a direct role in curly-leaf pondweed cover, except Portage Lake. Plant removal was largely undetectable at the whole-lake scale in all lakes except in South Center and Portage Lake where it constituted less than 10% of the area less than 15 feet in both lakes. In Portage Lake, a lake vegetation management plan that targets curly-leaf pondweed for removal was implemented prior to the SLICE program.

Differences in climate variables and potential effects on curly-leaf pondweed growth

Initially, the marked decline of curly-leaf pondweed was unexpected because 2010 was considerably warmer across the state, especially during the growing season (Figure 7). In fact, ice cover was two weeks shorter in 2010 compared with 2009 and 5 weeks shorter in 2010 compared with 2008. Spring 2010 was especially warm (as indicated by spring growing degree-days) across select infested lakes as compared with both 2008 and 2009 (Table 5).

The snowy winters of 2009, 2010 and 2011 may provide key evidence into the potential cause of curly-leaf pondweed declines. Curly-leaf pondweed has a winter growth form that requires some minimal level of light and sediment oxygen for basal metabolism (Catling and Dobson 1985; Wu et al. 2009). Long periods of ice cover with heavy snowpack can inhibit light penetration and dissolved oxygen concentrations and thus may inhibit the

Table 5. Winter and spring conditions in sentinel lakes where changes in curly-leaf frequency were most pronounced. Normals are from National Weather Service monthly totals averaged over the years of 1971-2000 from the climate station closest to each sentinel lake.

Lake	Year	Ice On	Ice Off	Days With Ice	Dec - Jan Snowfall (in)	Dec - Jan Snow Normal (in)	Avg. Daily Spring Temp (°C)	Spring GDD (base 5 °C)
Pearl	2008	NA	NA	NA	15.3	19.7	10.1	280
	2009	12/11/2008	4/14/2009	123	23.5	19.7	10.6	418
	2010	12/5/2009	3/30/2010	116	23.5	19.7	12.8	532
Peltier	2008	11/28/2007	4/21/2008	145	21.9	20.3	12.7	312
	2009	11/26/2008	4/9/2009	133	30.6	20.3	14.02	478
	2010	12/6/2009	3/29/2010	114	22.8	20.3	NA	NA
Portage	2008	11/22/2007	5/3/2008	163	20.8	20.1	9.9	218
	2009	11/18/2008	4/22/2009	154	30.6	20.1	11.2	309
	2010	12/4/2009	3/26/2010	113	19.2	20.1	11.9	503
St. James	2008	11/14/2007	4/11/2008	149	13.1	18.9	NA	NA
	2009	11/21/2008	3/24/2009	122	39.0	18.9	12.9	469
	2010	12/5/2009	3/29/2010	115	36.8	18.9	NA	NA
St. Olaf	2008	11/29/2007	4/16/2008	139	18.4	24.2	NA	NA
	2009	12/8/2008	3/24/2009	105	29.7	24.2	13.2	440
	2010	12/10/2009	3/30/2010	111	33.2	24.2	13.9	545

viability of curly-leaf pondweed emerging from winter.

Above average early season snowfall during the winters of 2009, 2010 and 2011 in most lakes followed several previous ones that were below average (Figure 8). Qualitatively, it appears the snowier the preceding winter, the greater the decline in curly-leaf pondweed frequency. However, based on 2011 it appears an "asymptote" may be reached where curly-leaf pondweed frequency is sustained at levels similar to 2009 and 2010 (Figure 5).

Case study: Declines of curly-leaf pondweed surface growth in Pearl Lake

Pearl Lake is a 753-acre eutrophic lake in central Minnesota that mixes continually throughout the summer. Montrose Area Fisheries has mapped curly-leaf pondweed surface growth in Pearl Lake since 2008. Patterns in curly-leaf pondweed surface-growth, which is a better proxy for plant abundance than areal cover, showed much more pronounced declines than plant frequency or cover (Table 6) Large declines in surface growth were apparent despite only moderately higher early winter snowfall compared with normal (Table 6). Still, there was an appreciable increase in measured surface growth of curly-leaf pondweed in 2011 in Pearl Lake, compared with 2009 and 2010 (Table 6).

Curly-leaf and Water Quality

Based on observations from the Sentinel lakes no strong linear relationship between CLP frequency and summer TP was evident; however, there is a non-linear pattern that is consistent with anecdotal observations in other infested lakes. CLP frequency was always low in mesotrophic lakes, low to high in meso-eutrophic lakes, and low to moderate in hypereutrophic lakes (Figure 5). These patterns were consistent

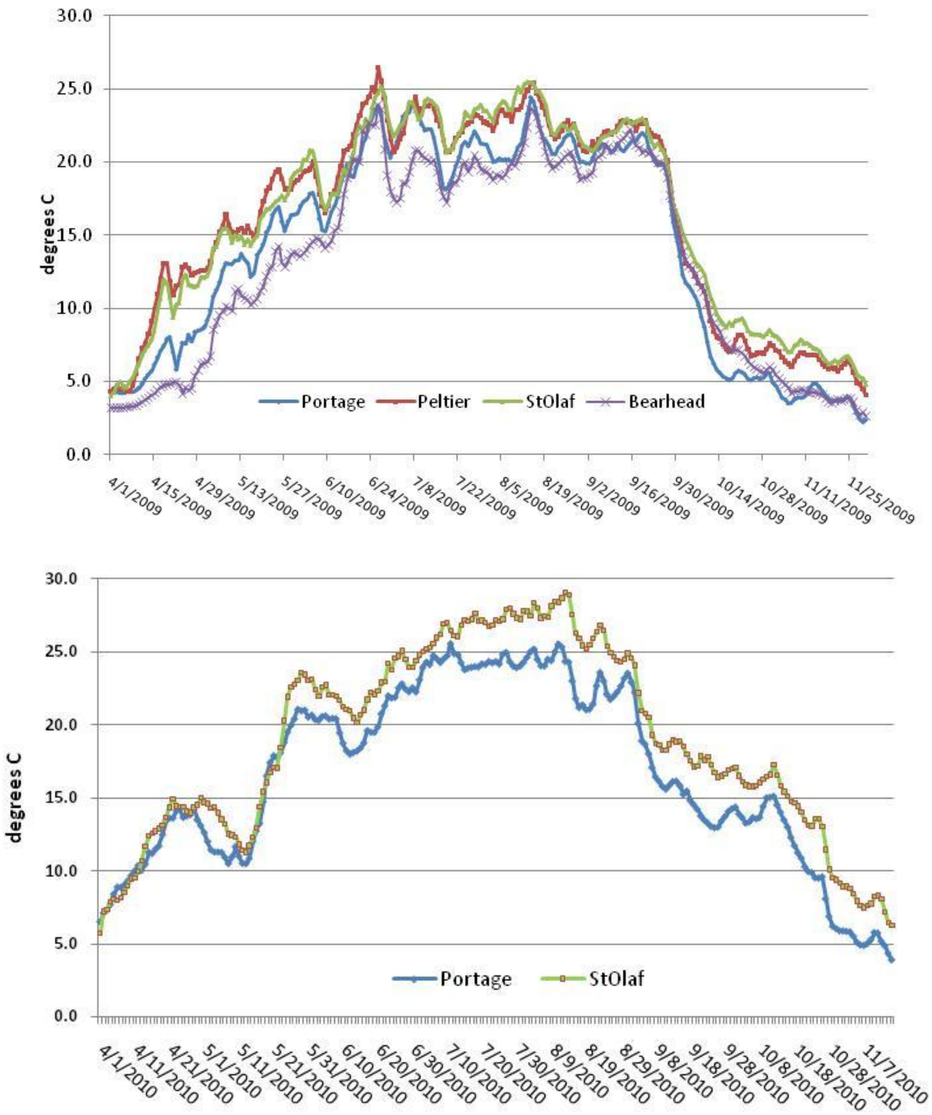


Figure 4. Surface water temperatures for select Sentinel lakes for 2009 and 2010.

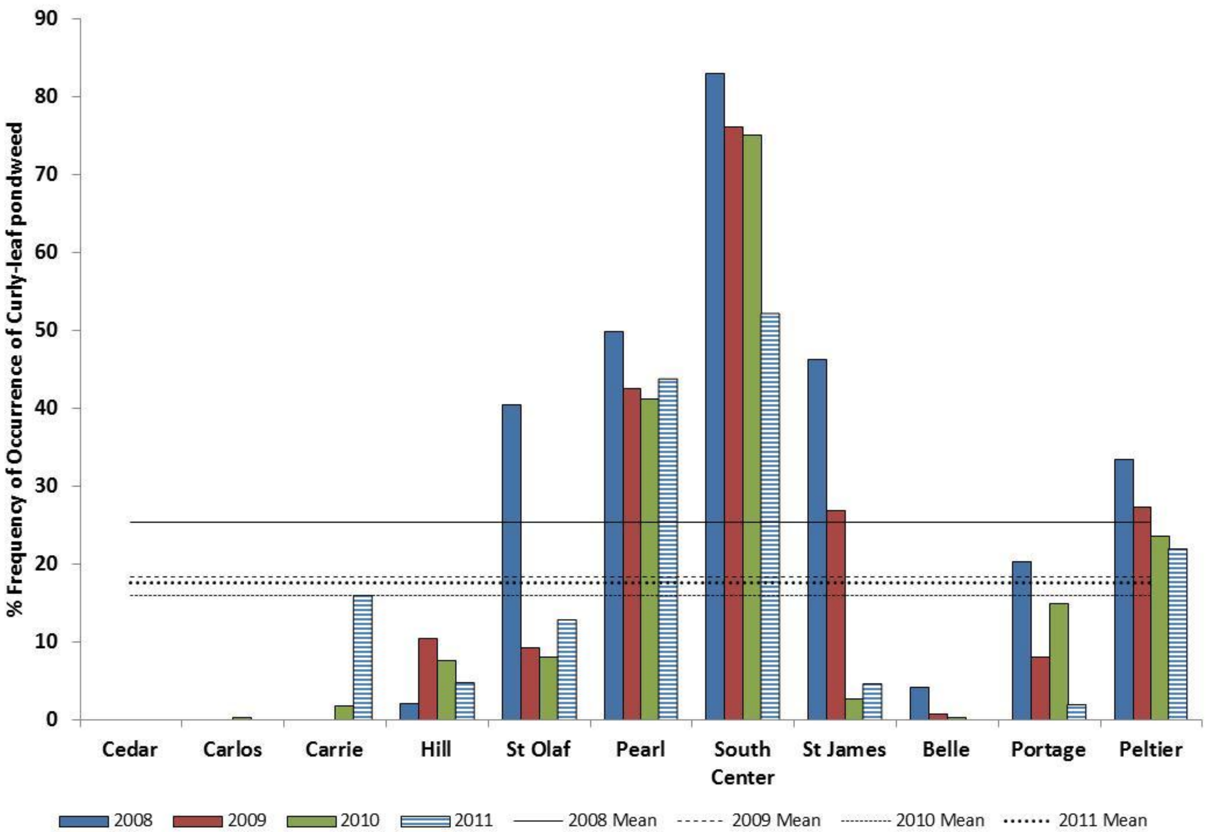


Figure 5. Curly-leaf pondweed frequency in depths less than or equal to 15 ft across 11 sentinel lakes, with curly-leaf pondweed in order of increasing total phosphorus. Yearly mean noted.

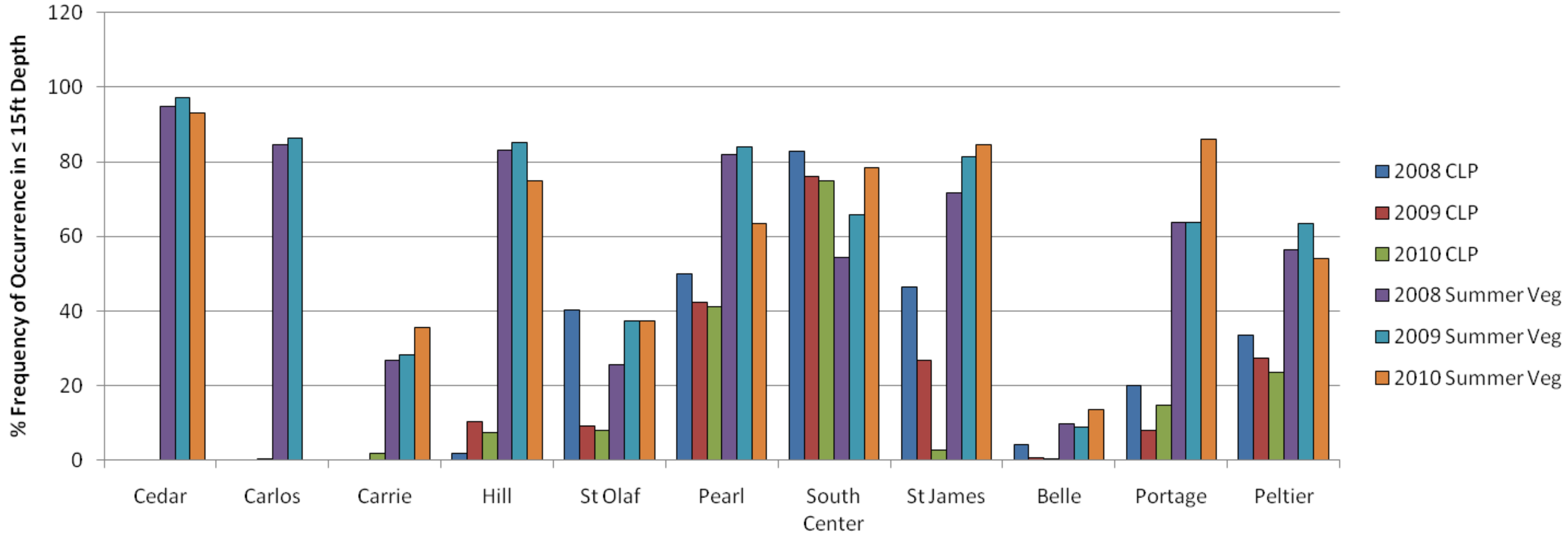


Figure 6. Curly-leaf pondweed frequency super-imposed with frequency of all vegetation sampled during the same summer in each lake with curly-leaf pondweed.

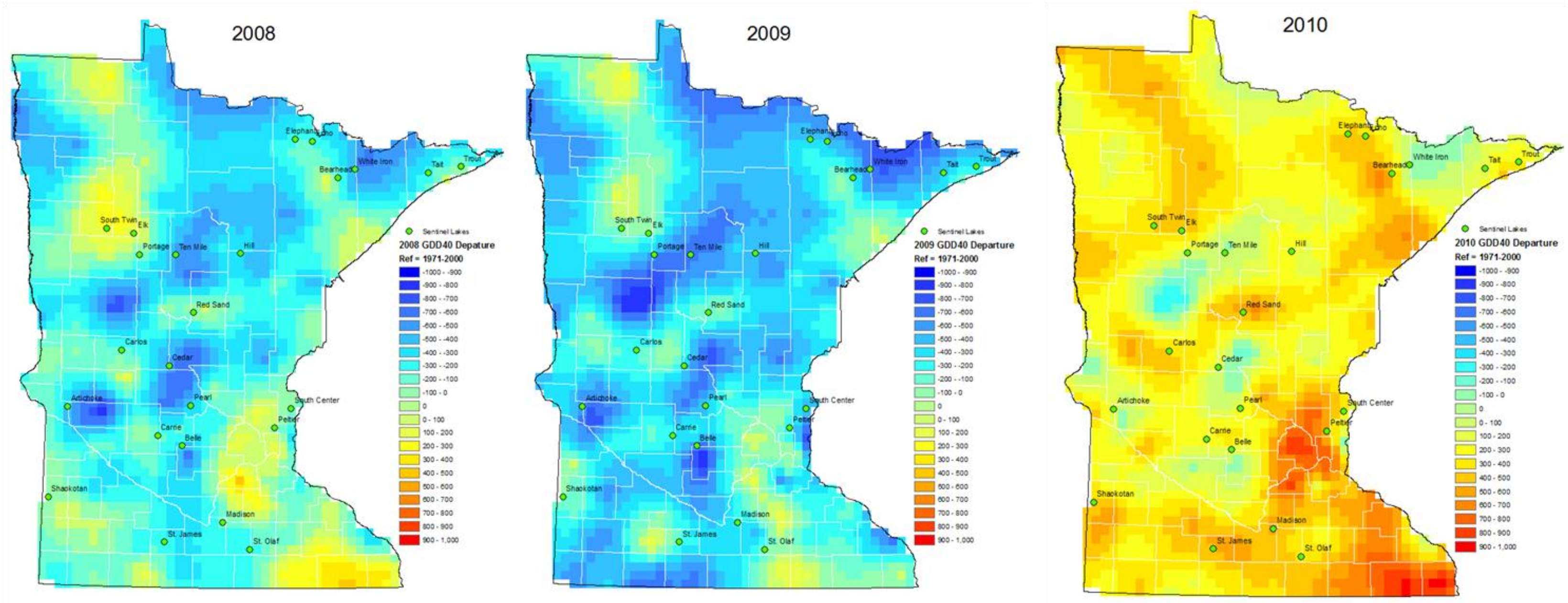


Figure 7. Departures from the 1971-2000 normal for Growing Degree Day Base 40° F for 2008-2010. Data acquired from Minnesota State Climatology Office.

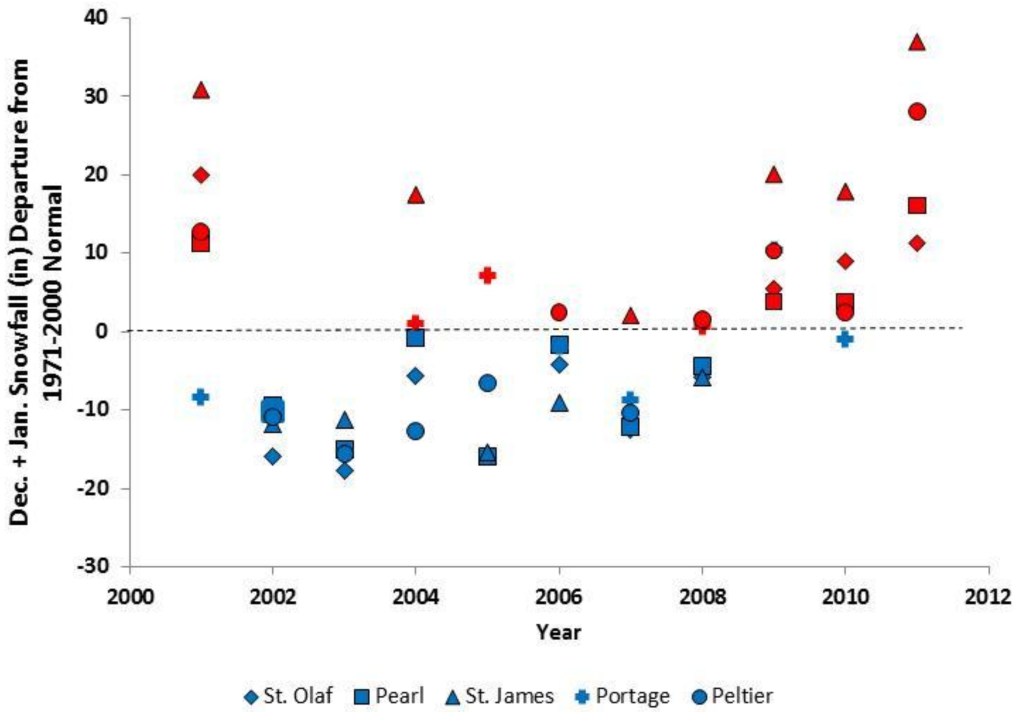


Figure 8. December + January snowfall (in) departures from 1971-2000 normal across several sentinel lakes infested with curly-leaf pondweed. Data are from the Minnesota State Climatology Office.

Table 6. Patterns of curly-leaf cover and surface growth in Pearl Lake, Stearns Co. Minnesota.

Year	Frequency (% occurrence ≤ 15ft)	Estimated Cover (% of whole lake)	Measured surface growth (% of whole lake)
2008	49.9	51.8	22.60
2009	42.5	35.8	0.75
2010	41.1	44.7	0.50
2011	43.8	39.2	5.50

among years as well. The statewide map (Figure 2) and list of occurrence by land type indicates the highest density of lakes with curly-leaf is in the Transition-Forest land-type, a region dominated by meso-eutrophic lakes. In contrast, density tails off in the Glacial Drift Northern Forest land type (typically mesotrophic lakes) and to the south in the prairie land type (predominately hypereutrophic lakes).

In addition to the relationship between trophic status and relative density of curly-leaf, there are some case-studies in Minnesota and Wisconsin that suggest that curly-leaf can have negative impacts on summer water quality conditions and promote algae blooms (James et al. 2002, Welling 2010). However, pilot studies and published research actually demonstrate negative effects of large-scale removal of curly-leaf pondweed or another common invasive plant, Eurasian watermilfoil *Myriophyllum spicatum* on summer water quality (Valley et al. 2006, Welling 2010) in eutrophic lakes. Below we highlight two recent case studies in Minnesota where negative effects of treatments on water quality and aquatic plants occurred.

Lake Benton (DNR ID# 41-0043-00). Lake Benton is a large but shallow lake in Lincoln County (1093 ha, max. depth = 2.7 m). Native aquatic plants have never been abundant in the lake over its entire surveyed history (1956 – present; MN DNR Fisheries unpublished survey data). Likewise, summer water clarity has typically been less than 1 m. Due to uncertainty in plant identification in previous Fisheries surveys and the time of year that they occurred (July and August), curly-leaf pondweed may have been misidentified or missed during sampling. Observations of abundant plants in June, followed by a lack of plant growth in August were first made by Fisheries staff and residents in 1988; however curly-leaf pondweed was not identified in the formal plant survey. The first time curly-leaf pondweed was specifically identified in plant surveys was 1992.

Curly-leaf pondweed did not receive explicit attention until a 2002 study of shallow southwest Minnesota lakes (Heiskary et al. 2003). The following observations were made in that study:

> "TP and chlorophyll-a averaged 157 and 39 µg/L respectively, which is rather typical for a Northern Glaciated Plains ecoregion lake. TP concentration was low in May and increased thereafter. In June the lake was almost completely covered by curly-leaf and it was difficult to find open water to sample. Vertical tows with a net revealed abundant large zooplankton under the plant canopy. Secchi was about 1.2 m on that date. By July 9, curly-leaf had senesced, TP and chlorophyll-a increased and Secchi declined to 0.3-0.4 m. Nuisance blooms of algae were evident from July through September with a peak in chlorophyll-a of 163 µg/L in August."

It remains unclear whether curly-leaf pondweed was a cause of algae blooms or whether curly-leaf pondweed was exploiting a perpetually turbid lake environment in which native plants could not exist.

In an attempt to test the hypothesis that removing curly-leaf pondweed early in the season could enhance native aquatic plant growth and improve water clarity, the Benton Lake Improvement District received a pilot grant from DNR to treat the whole lake with fluridone herbicide in 2005 -2008, then with Endothall in 2009 (Welling 2010). This resulted in a large reduction of curly-leaf pondweed frequency. Native plants throughout the lake remained sparse before and after treatments. Water clarity increased modestly after the second year of treatments (1.3 m), but declined back to the historic mean of less than 1 m after the third year of treatments (Welling et al. 2010). Patterns in summer total phosphorus levels since 1986 up to 2004 show steady decreases (yet still exceeding impairment thresholds; Heiskary and Wilson 2008; Figure 9). In four years following annual herbicide treatments, improvements in TP reversed and Chl-a also increased to levels that exceed all previous measures and impairment thresholds (Figure 9). Because water chemistry has not been monitored recently, we remain uncertain as to whether turbidity has changed over time from being algal dominated to suspended sediment dominated. Regardless, Welling (2010) demonstrated that native aquatic plant growth and water clarity was not improved in Benton (or other nutrient-rich Minnesota lakes) by removing large amounts of curly-leaf pondweed.

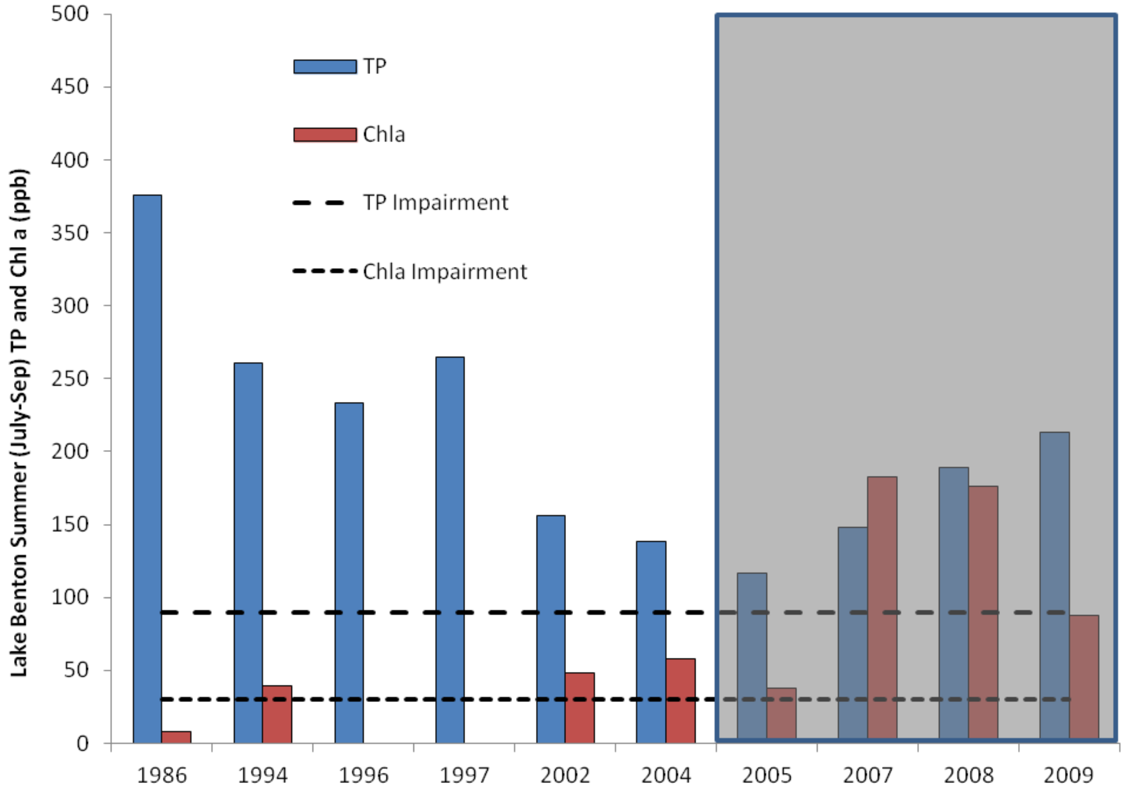


Figure 9. Total phosphorus and chlorophyll-a levels averaged over the post curly-leaf senescence months of July-September in Benton Lake (Lincoln Co) before and after annual bay or lake-wide herbicide treatments (gray box). State water quality impairment thresholds for TP and Chl a are denoted by the dashed lines.

Long-term patterns in vegetation-dependent game fish species such as northern pike and bluegill have usually been low compared with other Minnesota lakes similar to Benton (Schupp Lake Class 41) regardless of whether curly-leaf pondweed was present or being treated with herbicides. Benthivorous fish such as common carp and black bullhead *Ameiurus melas*, which often thrive in turbid Minnesota shallow lakes, have fluctuated over time in Benton Lake (MN DNR unpublished survey data). From a fish management perspective, temporary structural complexity provided by curly-leaf pondweed followed by algal turbidity is preferred to year-round algal and suspended sediment turbidity, which is a common response of a shallow windswept lake without plant growth and modest populations of benthivorous fish (Heiskary et al. 2003).

Silver Lake (DNR ID# 62-0001-00). Silver Lake is a small, relatively shallow eutrophic lake in North St. Paul. Prior to 1980, the lake experienced frequent winterkills of fish due to high nutrient levels and low oxygen during winter. Consequently, populations of bullheads, which are tolerant of low winter oxygen, were historically high (MN DNR unpublished survey data). High populations of black bullheads typically reduce water quality in lakes through their omnivorous feeding habitats and mobilization of phosphorus through excretion.

As part of an effort to improve water quality and maintain a viable fishery, a winter aeration system was installed in 1978, and with periodic improvements to the system, has operated continuously since. No significant winterkills have been reported since the aerator has operated and black bullhead declined from a high of 130 fish per gillnet in 1980 to zero in four fisheries surveys from 1995-2005 (MN DNR Fisheries unpublished data). Despite a lack of watershed restoration actions (John P. Hanson; Valley Branch Watershed District, personal communication), water quality improved appreciably since continuous records began in 1984 up to 2005 (Figure 10).

The history of curly-leaf pondweed invasion into Silver Lake is unclear. The first documented occurrence was in 1992, which is also the first time another invasive species, Eurasian watermilfoil was also documented (Osgood 1997). Although several earlier aquatic plant surveys occurred, they took place during periods of the summer when curly-leaf pondweed was likely senesced and thus undetectable. Although abundant "weed" growth and algae blooms were often recorded in the DNR Fisheries lake file for Silver Lake, as far back as 1954, species actually contributing to "nuisance" growth were not recorded.

Though water quality was good relative to Minnesota's lake eutrophication standards, a watershed management plan drafted in 2005 by the Valley Branch Watershed District and recommendations by Osgood (1997) suggested that efforts be made to remove curly-leaf pondweed and Eurasian watermilfoil to enhance native aquatic plants and further improve water quality. Accordingly, lake-wide treatments of the herbicides Triclopyr and Endothall occurred in 2007, 2008, and 2009 (Endothall only) to target curly-leaf pondweed and Eurasian watermilfoil (Welling 2010). Collectively these plants accounted for 70% frequency of plants, but native aquatic plants were also frequent (Welling 2010).

In subsequent years following treatment, native aquatic plants and total vegetation cover and water clarity have declined (Welling 2010). In fact, after a 20-year improvement of water quality conditions that brought the lake within water quality standards, lake phosphorus levels are now back to the impaired levels of the mid 1980's (Figure 10). Further, shortly after the herbicide treatments in 2007, chlorophyll reached a record high, and through 2010 remained above water quality standards (Figure 10). These finding suggest that repeated herbicide treatments may have triggered a water quality regime shift (Scheffer and Carpenter 2003; Contamin and Ellison 2009). Given the difficulty in reversing this shift in shallow lakes, meeting water quality standards could require increased efforts to reduce both external and internal phosphorus loading (Scheffer and Carpenter 2003; Contamin and Ellison 2009).

These case studies show that removing curly-leaf pondweed without other in-lake and watershed management practices occurring simultaneously that reduce phosphorus loading may not improve native plant or water quality conditions. In fact, a sole focus on killing curly-leaf pondweed in lakes, especially where the plant is abundant (exact threshold quantities remain unknown) may carry more risks of harmful effects to water quality and fish habitat than leaving the plant unmanaged.

Does curly-leaf pondweed influence seasonal patterns in trophic status in Sentinel Lakes?

Data from select Sentinel lakes provides an opportunity to see what might be learned with respect to seasonal patterns in trophic status (water quality) as it may relate to curly-leaf growth and senescence. In deeper lakes, which are typically well-mixed in April and May, following ice-out and wind-mixing, TP and chlorophyll-a (Chl-a) are often quite high. Chl-a is high because of diatoms that prosper in the cool nutrient rich water. As deep lakes stratify and diatoms settle to the bottom of the lake, reductions in TP and Chl-a are often noted in May and June (Figure 11). If the lake remains stratified over the summer, epilimnetic TP is often stable or slightly declining over the summer (absent any major summer loading events). This decline is a reflection of algal uptake of P and the natural sedimentation processes. While internal recycling of P will occur at the sediment-water interface, this source of P is often entrained in the hypolimnion and does not mix, to a significant degree, with the surface waters until fall overturn. Chl-a often increases over the summer as the waters warm and algal dominance shifts from diatoms to blue-greens. As algal concentrations increase, Secchi will decrease (Figure 11).

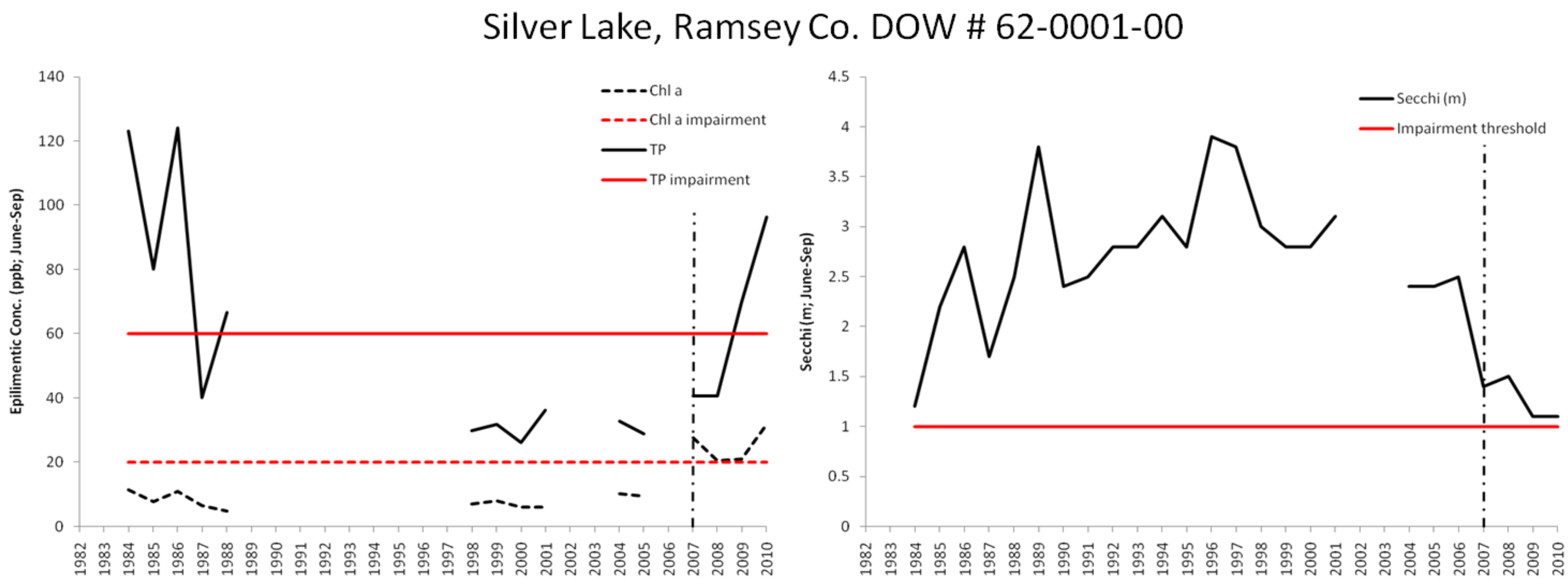
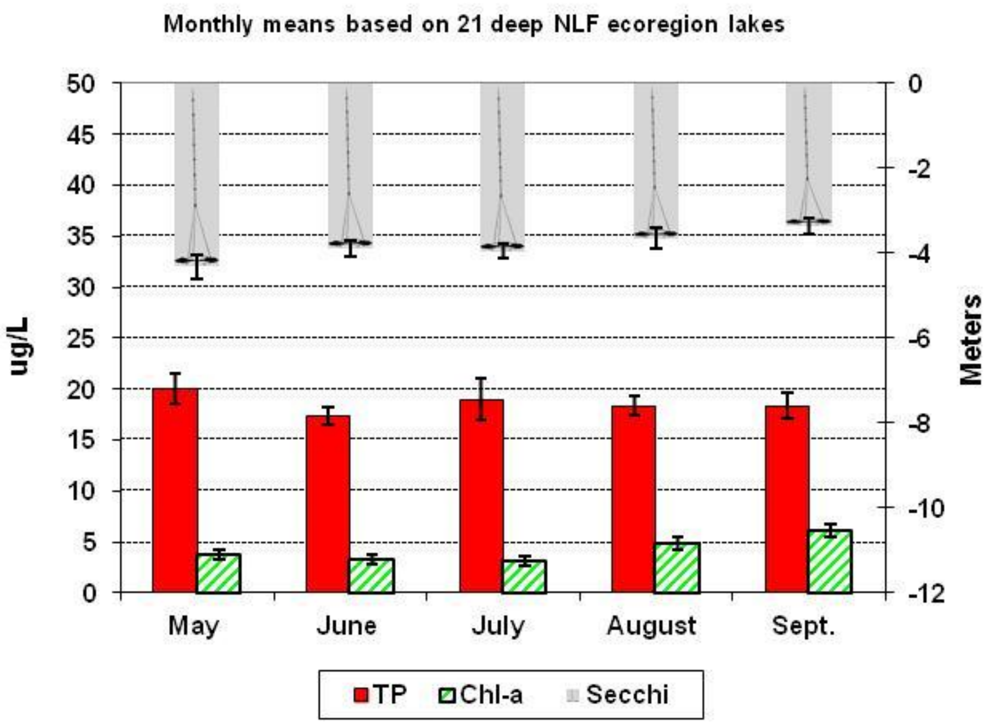


Figure 10. Historic water quality trends in Silver Lake (Ramsey Co.) before and after repeated whole-lake herbicide treatments of Triclopyr and Endothall to kill curly-leaf pondweed and Eurasian watermilfoil starting in 2007. Red lines indicate applicable lake eutrophication standards (Heiskary and Wilson 2005).



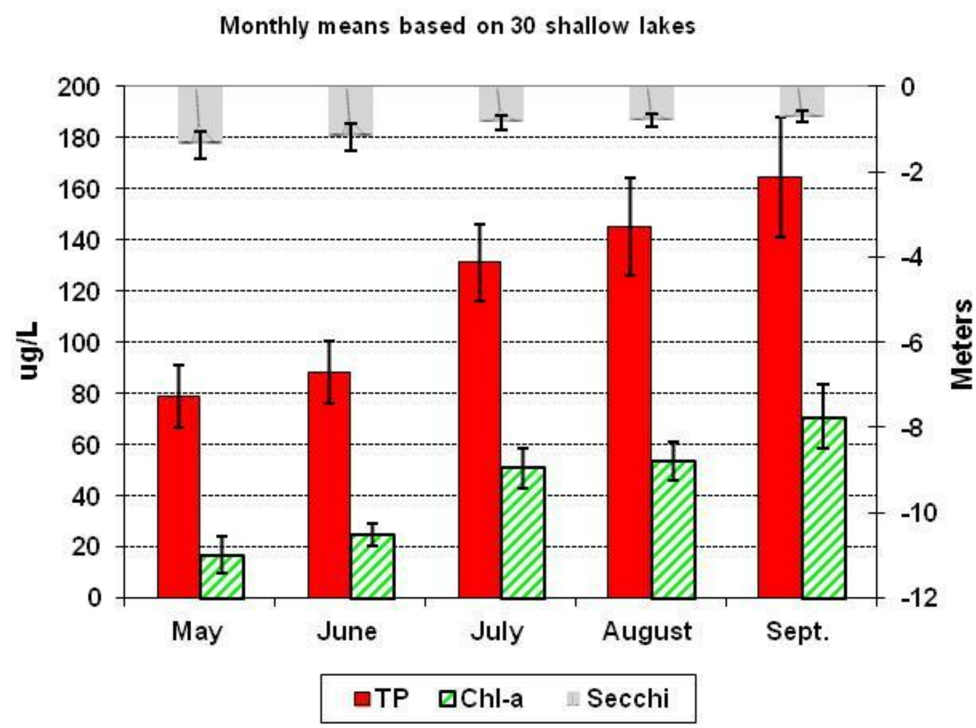


Figure 11. Monthly mean TP, Chlorophyll-a (left axis) and Secchi (right axis) for Deep and Shallow Lakes. Note difference in scale for the two charts.

Shallow lakes exhibit a somewhat different pattern. Again, TP and Chl-a are often high in April followed by a decline in May. Chl-a in May and sometimes early June may be relatively low because of zooplankton grazing and competition with rooted plant growth. As summer progresses a marked increase in both TP and Chl-a is often observed (Figure 11) that is often driven by internal processes. Various factors contribute to "internal" recycling and may include: curly-leaf pondweed senescence, frequent wind mixing that may entrain P-rich sediments into the water column, bioturbation from benthivorous fish such as carp and bullhead, increased temperatures (>17-21° C) that promote bacterial decomposition and various other factors (Heiskary and Wilson, 2005). Because shallow lakes may incorporate several of these factors it can be difficult to isolate any single factor as a specific cause. In response to increased TP, Chl-a increases dramatically over the summer and these blooms are often dominated by blue-green algae, which accumulate near the surface. Secchi declines in response to increased algae concentrations.

Given the multiple drivers that may promote internal recycling in shallow lakes it can be challenging to isolate the role of curly-leaf. However, seasonal patterns in the Sentinel lakes provide a basis for among lake comparisons and an opportunity to view these changes relative to the gradient of curly-leaf in these lakes. A summary for several deep (Figure 12) and shallow Sentinel lakes (Figures 13 and 14) that have curly-leaf are provided for this purpose.

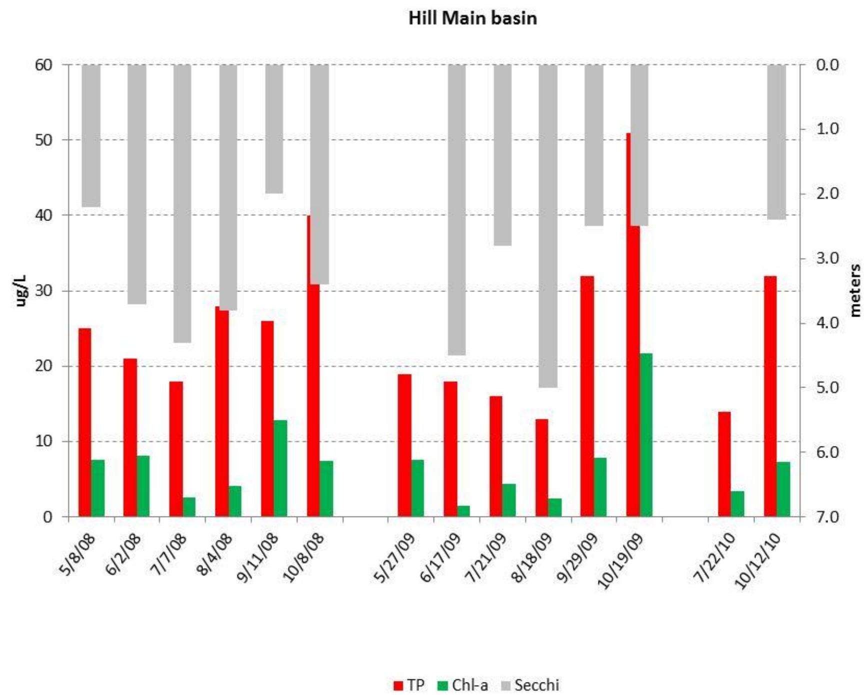
Deep lakes

Hill (DNR ID# 01-0142-00). Hill Lake is characterized by two distinct basins: the deeper northeast or main basin and the smaller and shallower southwest basin (Table 2). The main basin drains to the southwest basin and in fact, much of the Hill Lake watershed drains directly into the southwest basin. Hill Lake had relatively low curly-leaf cover during 2008-2010 (Figure 5). The seasonal TP pattern for the main basin is fairly consistent with the deep lake pattern (Figure 12). The pattern in the southwest basin is more variable and does not consistently mirror either the deep or the shallow lake pattern (Figures 11 and 12). The seasonal increase in 2009 may be the product of rain during July-September and there is no clear indication that curly-leaf senescence has a distinct influence on in-lake TP in either basin.

Carrie (DNR ID# 34-0032-00). Carrie Lake is a small marl lake (Table 2) with low TP and Chl-a, which stratifies during the summer months. Its transparency is low relative to TP and Chl-a (Table 2), which is presumably caused by very fine calcium carbonate particles suspended in the water. MPCA staff report that marl deposits are quite evident on plants and substrates in the lake and the marl is readily resuspended when sediments are disturbed. Curly-leaf pondweed is present at very low levels in the lake (Figure 5) and it does not appear to have an influence on TP or Chl-a (Figure 12).

St. Olaf (DNR ID# 81-0003-00). St. Olaf Lake is a small (37 ha), relatively deep (9.1 m) lake in southern Minnesota (Figure 12). St. Olaf had relatively high cover of curly-leaf pondweed in 2008 but experienced a substantial decline in 2009 and 2010 (Figure 5). St. Olaf's seasonal TP transition is quite consistent with that observed in deep lakes in that TP initially declines from spring into early summer (Figures 11 and 12). There is no indication that the distinct differences in curly-leaf abundance among 2008 and 2009 had a significant influence on the trophic status of St. Olaf in any of the three years.

South Center (DNR ID# 13-0027-00). South Center Lake is a relatively large (336 ha) and deep (30.5 m) lake located just north of the Twin Cities metro area (Table 2). Two sites were monitored in the lake – one in the north over the site of maximum depth and one in the southwest in a shallower portion of the lake near a productive littoral fringe (Engel et al. 2011). South Center had the highest frequency of curly-leaf of any of the lakes (Figure 5) but the majority was found in the very shallow eastern basin that is somewhat separate from the water quality monitoring sites. South Center's seasonal TP pattern at both sites (Figure 12) is not consistent with that for deep lakes (Figure 11). The southwest site, which is located near the littoral fringe where curly-leaf is present, exhibited an increase in TP in 2008 (Figure 12). The recent invasion



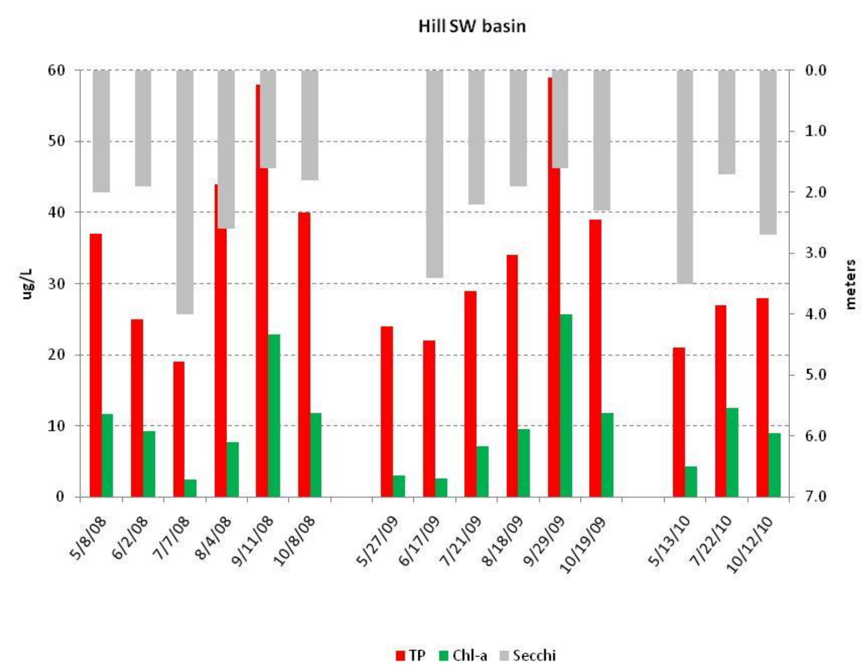
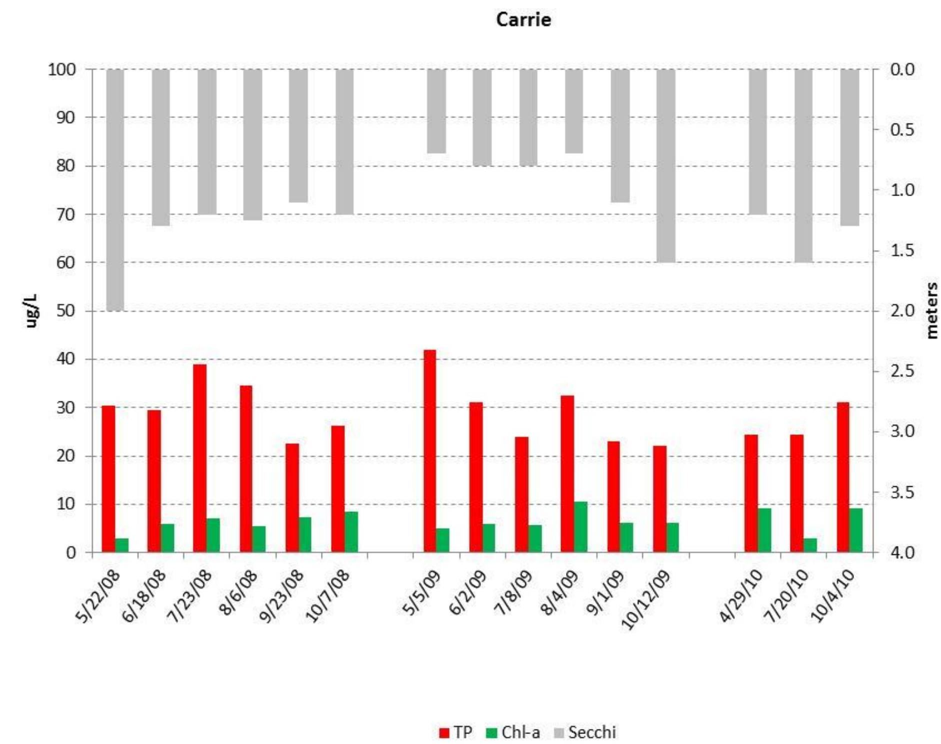


Figure 12. (1 of 3) Trophic status patterns for deep Sentinel lakes with curly-leaf pondweed: Hill (main & SW basin), Carrie, St. Olaf, and South Center (main & SW end). Note Hill main basin is deep and stratified, whereas SW basin is shallow and well mixed.



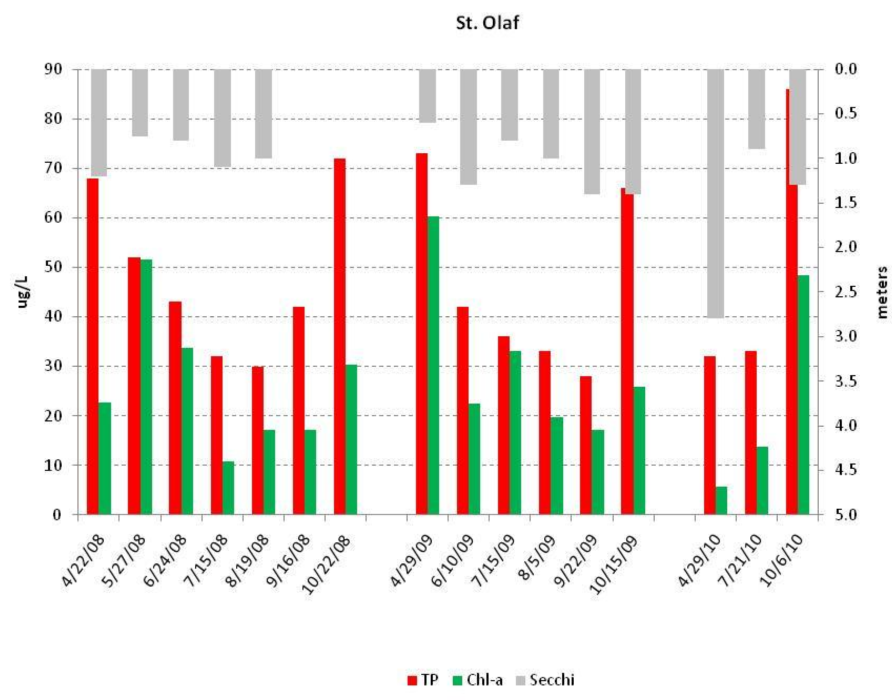
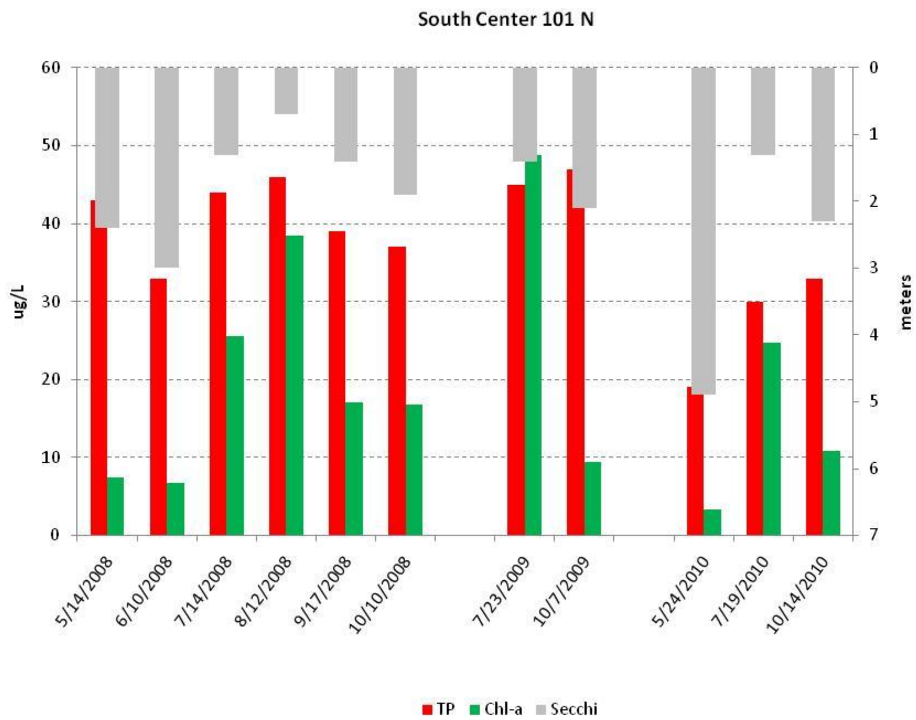


Figure 12. (2 of 3) cont.



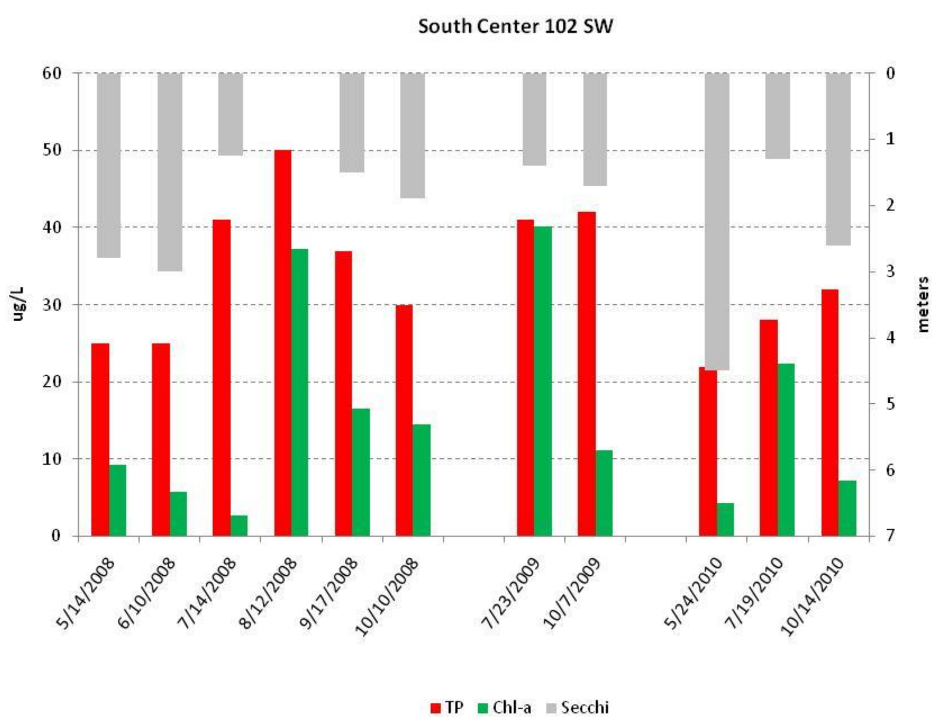
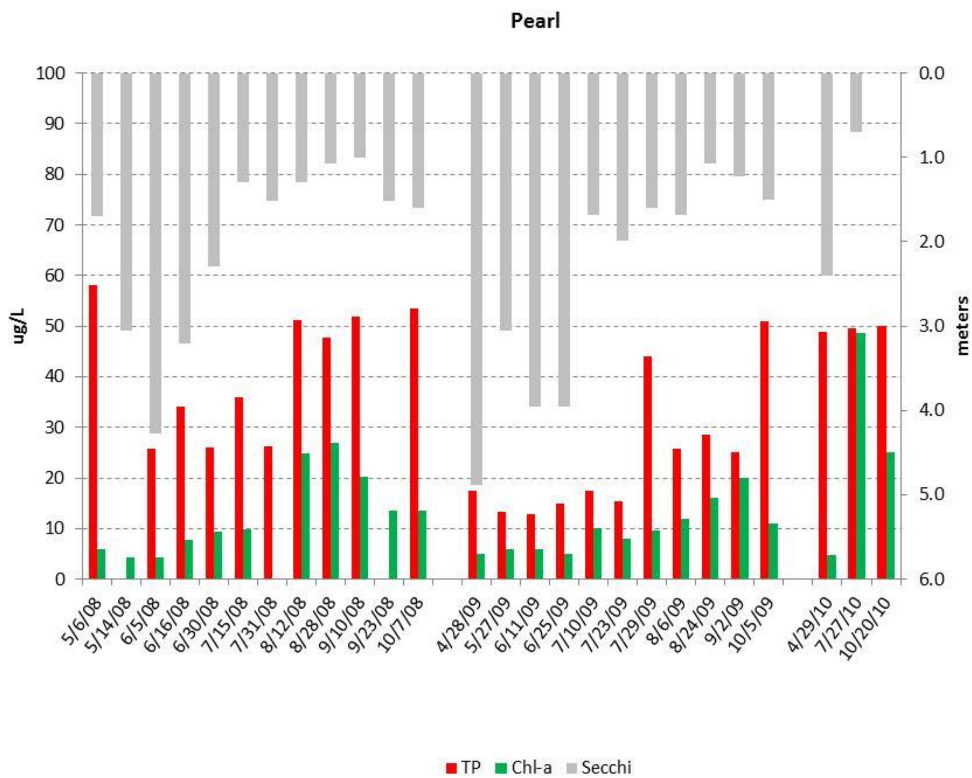


Figure 12. (3 of 3) cont.



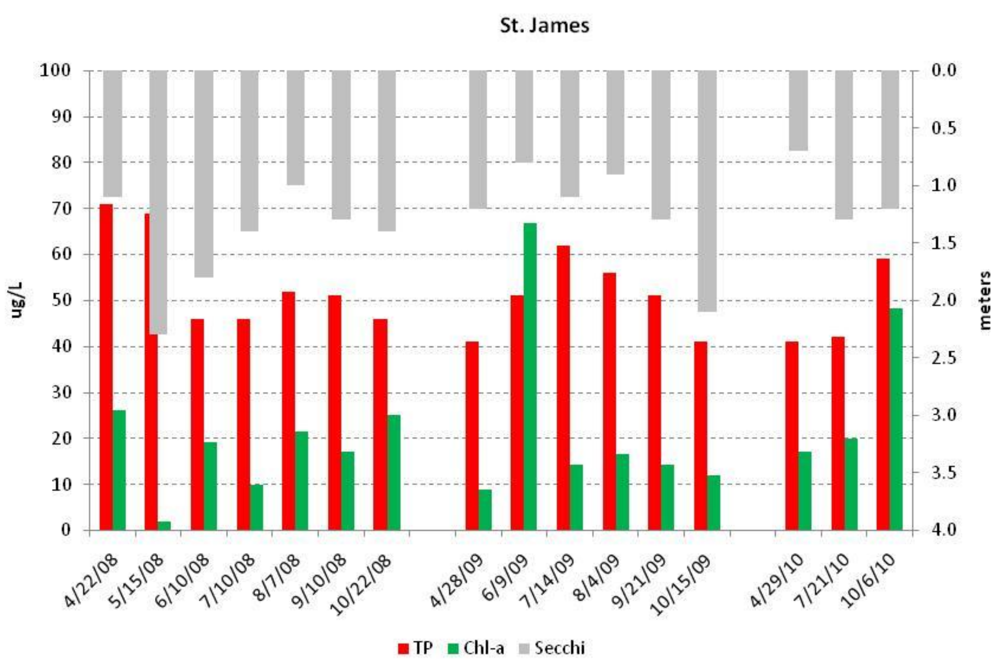
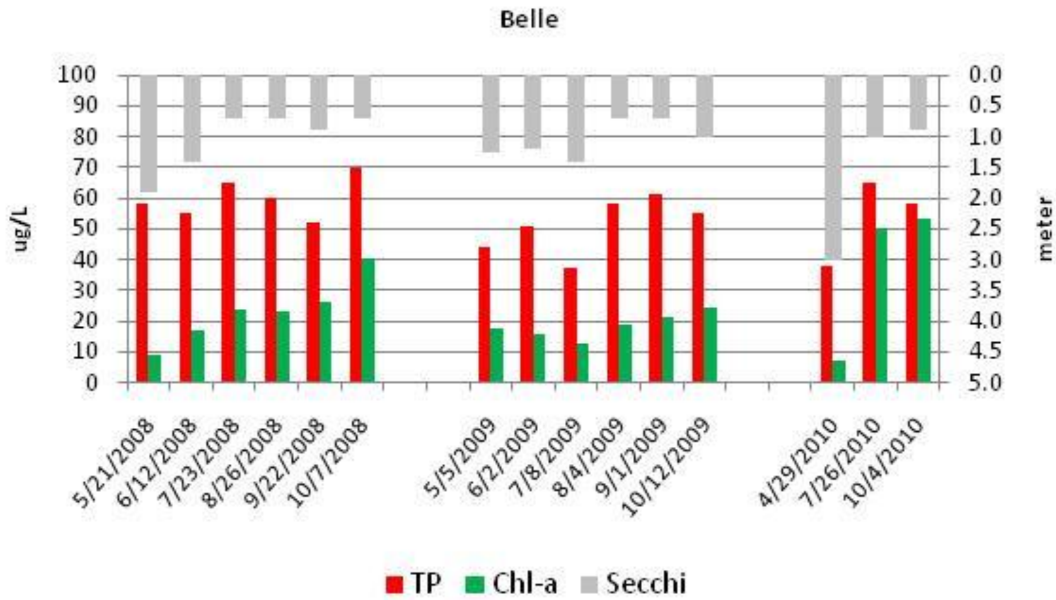


Figure 13. (1 of 3) Trophic status patterns for shallow Sentinel lakes with curly-leaf pondweed: Pearl, St. James, Belle, Portage and Peltier.



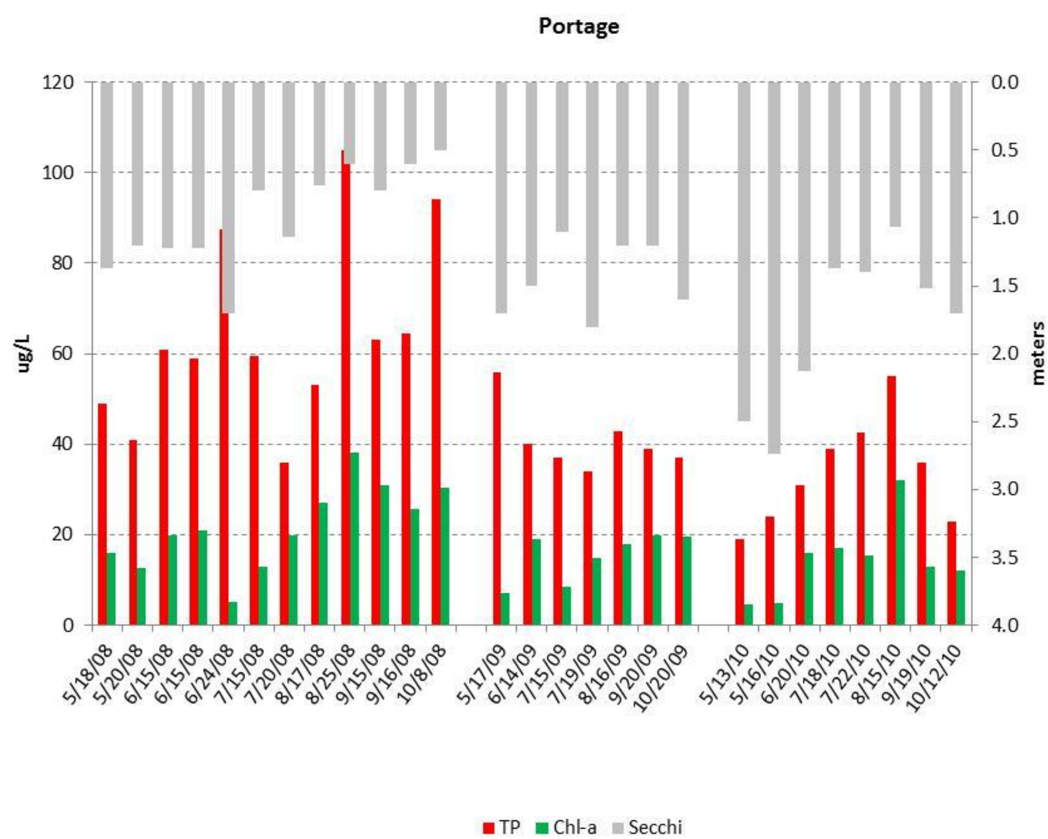


Figure 13. (2 of 3) cont.

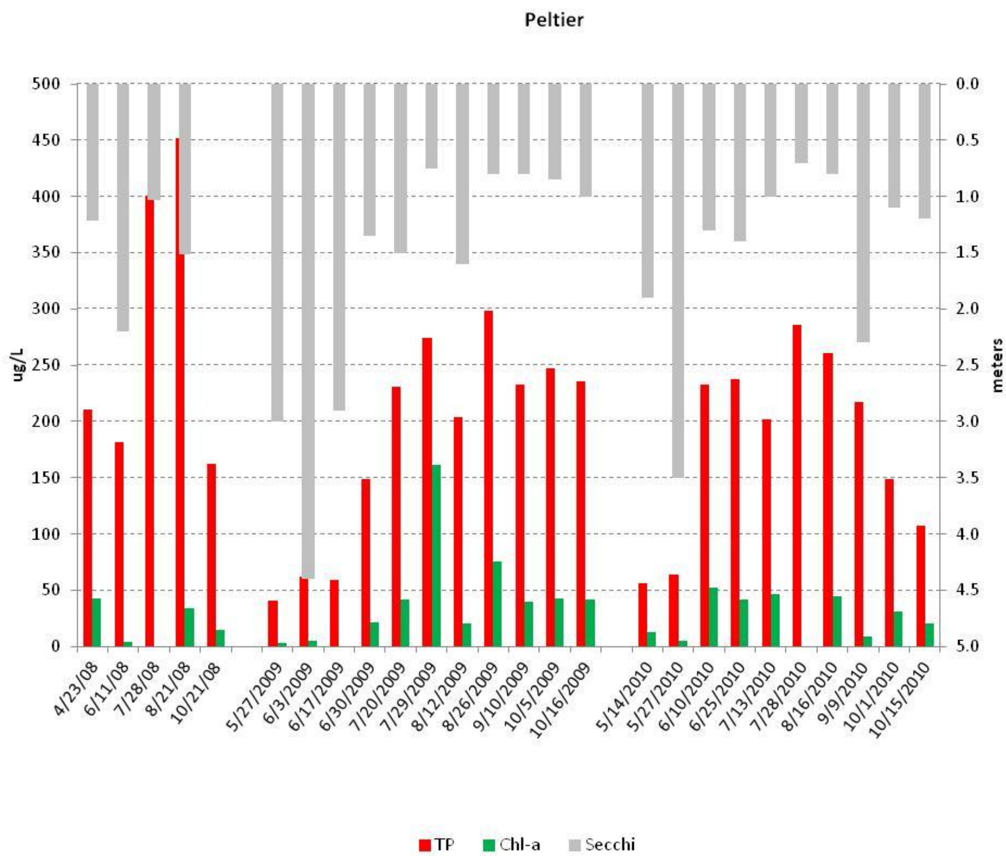


Figure 13. (3 of 3) cont.

and spread by hybrid milfoil (*M. sibiricum x M. spicatum*) in 2009 further confound any relationship between curly-leaf pondweed cover and water quality (see Engel et al. 2011).

Shallow lakes

Pearl (DNR ID# 73-0037-00). Pearl Lake is a shallow lake located near St. Cloud in central MN. It has moderate TP and Chl-a (Table 2). Pearl has the second highest amount of curly-leaf of any of the Sentinel lakes (Figure 5). Based on intensive monitoring during 2008 and 2009 Pearl exhibited a seasonal increase in TP (Figure 13) that is quite consistent with other shallow lakes (Figure 11). Curly-leaf senescence likely contributes to the mid-summer increase in TP and Chl-a; however this is likely moderated to some degree by the relatively abundant summer vegetation; especially *Chara* sp. (Kufel and Kufel 2002; Figure 6).

St. James (DNR ID# 83-0043-00). St. James Lake is a shallow lake in southern Minnesota. It had a high frequency of curly-leaf in 2008 but much lower levels in 2009 and 2010 (Figure 5). Seasonal TP increases in 2008 and 2009 (Figure 13) are evident but not as pronounced as in typical shallow lakes (Figure 11). In 2010, when curly-leaf was at a very low level (Figure 5), there was no difference among the April and July TP and Chl-a concentrations (Figure 13). One reason for a lack of a significant TP increase following curly-leaf senescence may be the high frequency of vegetation that is present during the summer (Figure 6), which is in contrast to shallow lakes that have minimal vegetation following senescence.

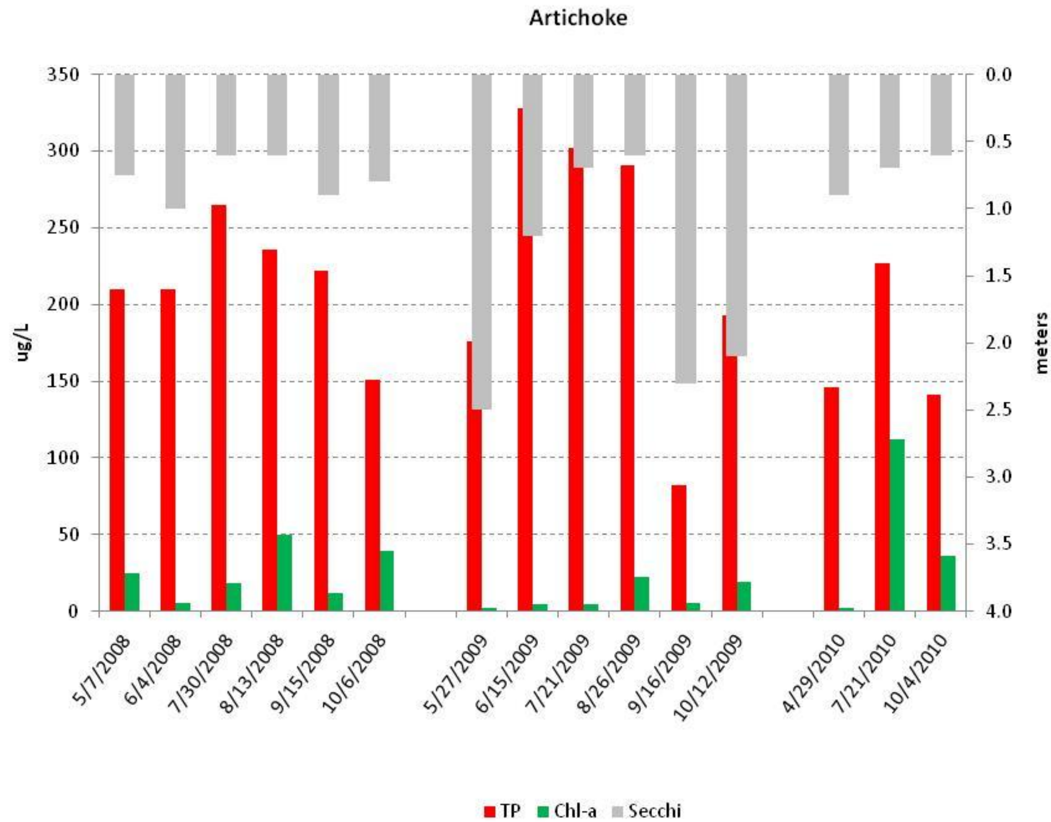


Figure 14. Trophic status patterns for Artichoke Lake, a shallow Sentinel lake with minimal curly-leaf pondweed.

Belle (DNR ID# 47-0049-01). Belle Lake is a relatively large, shallow lake in south central Minnesota. It has moderate TP concentration similar to several of the other shallow lakes (Table 2). Curly-leaf is present but at very low levels (Figure 5). Belle exhibits subtle increases in TP over the summer as compared to lakes with higher densities of curly-leaf (e.g., Pearl and Portage; Figure 13) and overall has very low plant density (Figure 6). Sandy substrates, large wind fetch and presence of carp have all been offered as reasons for low plant density in Belle Lake (Anderson et al. 2011). Together, these mechanisms likely limit both native and invasive plants in Belle Lake.

Portage (DNR ID# 29-0250-00). Portage Lake is a shallow and moderate-sized lake in north central Minnesota (Table 2). It has high TP for a lake in the Northern Lakes and Forest (NLF) ecoregion and is on the impaired waters list for excessive nutrients. Curly-leaf pondweed has been present in the lake since at least mid-1990. While at lower densities than some of the other Sentinel lakes, it has been a significant management issue for lakeshore residents since the early 2000s (O'Hara et al. 2009), presumably because the plant grows to the surface whereas native plants often do not. Despite the presence of curly-leaf pondweed, the plant community in Portage has historically been diverse with high cover of *Chara* sp. (O'Hara et al. 2009). Because of the potential for water quality improvements with targeted removal of curly-leaf pondweed, a lake vegetation management plan was approved by DNR in 2007 (before designation as a sentinel lake) to target the removal of curly-leaf pondweed from the lake with herbicides. Since 2008, curly-leaf pondweed growth in 5-13% of the lake has been treated in early spring with herbicides (O'Hara et al. 2009). Distinct seasonal increases in TP and Chl-a were evident in 2008 and 2010, but not 2009 (Figure 13). Consequently, these data do not suggest curly-leaf pondweed drives water quality patterns in Portage Lake. Furthermore, results suggest herbicide treatments targeting curly-leaf pondweed have thus far had relative benign effects on the lake's water quality regime and native plants. The relatively low pre-treatment abundance of curly-leaf pondweed coupled with high cover of *Chara* and cooler water temperatures of this northern lake are potentially important factors preventing the negative outcomes observed in the earlier case-studies in Benton and Silver lakes.

Peltier (DNR ID# 02-0004-00). Peltier Lake is a shallow nutrient-rich lake with a very large watershed in the northern Metro area (Table 2). Curly-leaf pondweed has been present in the lake since at least 1982 (Lindon et al. 2009). Of the Sentinel lakes with curly-leaf pondweed, it is intermediate in the relative density of the plant (Figure 5). Peltier exhibits different responses to the curly-leaf infestation between the south basin that is almost void of plants following senescence and the north basin that has dense coontail beds throughout much of the summer (Lindon et al. 2009). Based on MPCA (2008) and Rice Creek Watershed District (2009-2010) data from the south basin, there is a very distinct increase in TP in July (Figure 13). Since this coincides with curly-leaf senescence and surface water temperatures of 24-25 C it seems reasonable to assume that curly-leaf senescence is at least partially responsible for this increase. Severe nuisance blooms of colonial blue-green algae accompany this seasonal increase in TP.

Artichoke (DNR ID# 02-0004-00). Artichoke Lake in Big Stone County is very large and shallow (Table 2). Its organic sediments, large fetch, and low transparency are not conducive to rooted plant growth and as a result plant density is quite low, and during the last decade has had negligible curly-leaf pondweed (DNR Fisheries unpublished survey data; Table 2). However, during the 1990s (when the plant was first observed), curly-leaf pondweed was very dense in the north basin (DNR Fisheries unpublished survey data). Artichoke Lake does exhibit mid-summer increases in TP (Figure 14) similar to other shallow lakes; however, these increases are not related to curly-leaf pondweed. Rather, internal recycling of phosphorus is likely driven by elevated temperature, pH and sediment resuspension.

Conclusions and Management Implications

Curly-leaf pondweed is a long-established invasive aquatic plant species that is widespread throughout Minnesota. The plant thrives in disturbed lake environments with moderate to high total phosphorus concentrations and is hypothesized to cause algae blooms after the plant dies back in midsummer. Given its potential to affect water quality and fish habitat, curly-leaf pondweed has been monitored in 11 infested sentinel lakes since 2008. Although curly-leaf pondweed cover varied as a function of lake productivity, it was always sparse in the mesotrophic sentinel lakes and typically most abundant (in terms of cover) in the eutrophic sentinel lakes.

An analysis of curly-leaf growth and density, over three years, found unexpected recent declines in curly-leaf pondweed cover across this network of infested sentinel lakes. Possible reasons behind the decline and hypotheses that should be investigated are offered. We also explored the influence of curly-leaf senescence on lake water quality across a range of lakes where the plant occurs. The relationship between curly-leaf pondweed and water quality varies substantially among lakes and clearly defining "cause and affect" can be difficult. Nevertheless, we find little evidence supporting curly-leaf pondweed as a driver of water quality regimes in Minnesota, and thus lake managers should not expect water quality enhancements by focusing exclusively on killing curly-leaf pondweed without simultaneous, long-term measures to reduce internal and external phosphorus loads

Potential effects of climate on curly-leaf pondweed growth and range expansion. Winter severity, in terms of early season snowfall, is potentially one of several factors limiting curly-leaf pondweed viability and probability of reaching high abundance levels within infested lakes. We hypothesize that the warm, low-snow years of the mid 2000s may have benefitted the viability of curly-leaf pondweed plants emerging from winter and resulted in growth in infested lakes that was above normal. We speculate that during this period curly-leaf pondweed growth started to become more noticeable in northern Minnesota lakes already infested and resulted in new successful (albeit unintentional) introductions.

The winters of 2008-2010 were snowier than normal in most parts of Minnesota, and we observed marked declines in curly-leaf cover, and in one lake where it was mapped, surface growth. Despite recent snowy winters statewide, long-term trends show different precipitation patterns depending on latitude. In the southern part of the state south of the Minnesota River (climate divisions 7-9), winter precipitation has more often fallen as rain; whereas the opposite has been observed north of a line intersecting the headwaters of the Mississippi River (climate divisions 1-3; Figure 15).

Downscaled climate change models for Wisconsin predict shorter periods of ice-cover and less snowfall during winter (Wisconsin's Changing Climate: Impacts and Adaptation 2011). If past patterns in Minnesota hold, then we expect large contrasts in under-ice conditions as one travels from south to north. In the north, winter snowpack on lakes may limit light and oxygen and thus habitat conditions for curly-leaf pondweed regardless of shorter ice-cover. In the south, where more winter precipitation may fall as rain, habitats may become more viable for curly-leaf pondweed. The net effect may be a slow northerly migration of the snow-rain line, bringing with it better habitat conditions for curly-leaf pondweed and other evergreen invasive plants like Eurasian watermilfoil.

Still, lake productivity does appear important as an additional regulator of curly-leaf pondweed growth, and management actions that strengthen the resilience of clear water regimes in lakes (e.g., minimizing watershed runoff and avoiding removal of aquatic plant cover; Carpenter and Cottingham 1997) are important hedges against curly-leaf pondweed dominance of the littoral zone.

Where resilience in the clear-water state has been lost, as is the case in many central and southern Minnesota lake systems (e.g., south basin of Peltier, Benton, and Silver), expectations and approach toward managing curly-leaf pondweed may need to be adjusted. Many central and southern Minnesota lakes and their watersheds have been fundamentally altered to facilitate agriculture and urban development (Blann et al. 2009; Jackson and Pringle 2010). In many cases, these alterations have slowly reduced the habitat suitability for native plants and animals and created environments more suitable for invasive plants and animals. Turning back the clock in lake systems (that behave like watershed sinks) is incredibly costly and difficult, if not impossible (Carpenter and Cottingham 1997). Rather, in systems characterized by irreversible changes to hydrologic, nutrient or climate regimes we must explore approaches to deriving ecosystem “goods and services” from different species assemblages (Hobbs et al. 2006; Seastedt et al. 2008; Schlaepfer et al. 2011). The goods provided by curly-leaf pondweed compared with a lake with little plant growth (if that is the choice) include promoting water quality in compliance with the Federal Clean Water Act, and habitat for native fish species and waterfowl. The services provided include fishing, bird watching, and waterfowl hunting. In contrast, noxious algae blooms harmful to human health (and thus in violation of the Clean Water Act) and undesirable benthivorous fish typify a lake with no plants. The reduction of these goods and services must be weighed against the increased access to motorized boat recreation that would come with eradication of all plants. Environmental Laws and Public Trust Doctrine have generally favored protecting the long-term integrity of habitats over conflicting human uses and promote lower impact human uses.

Invasive aquatic plant management that is solely focused on removing invasive plants and does not consider new lake ecosystem constraints that prevent self-correction after the invasive is removed, may lead to unintended net reductions in ecosystem goods and services (Rinella et al. 2009; Kovalenko et al. 2010). In other words, the benefits of removing the

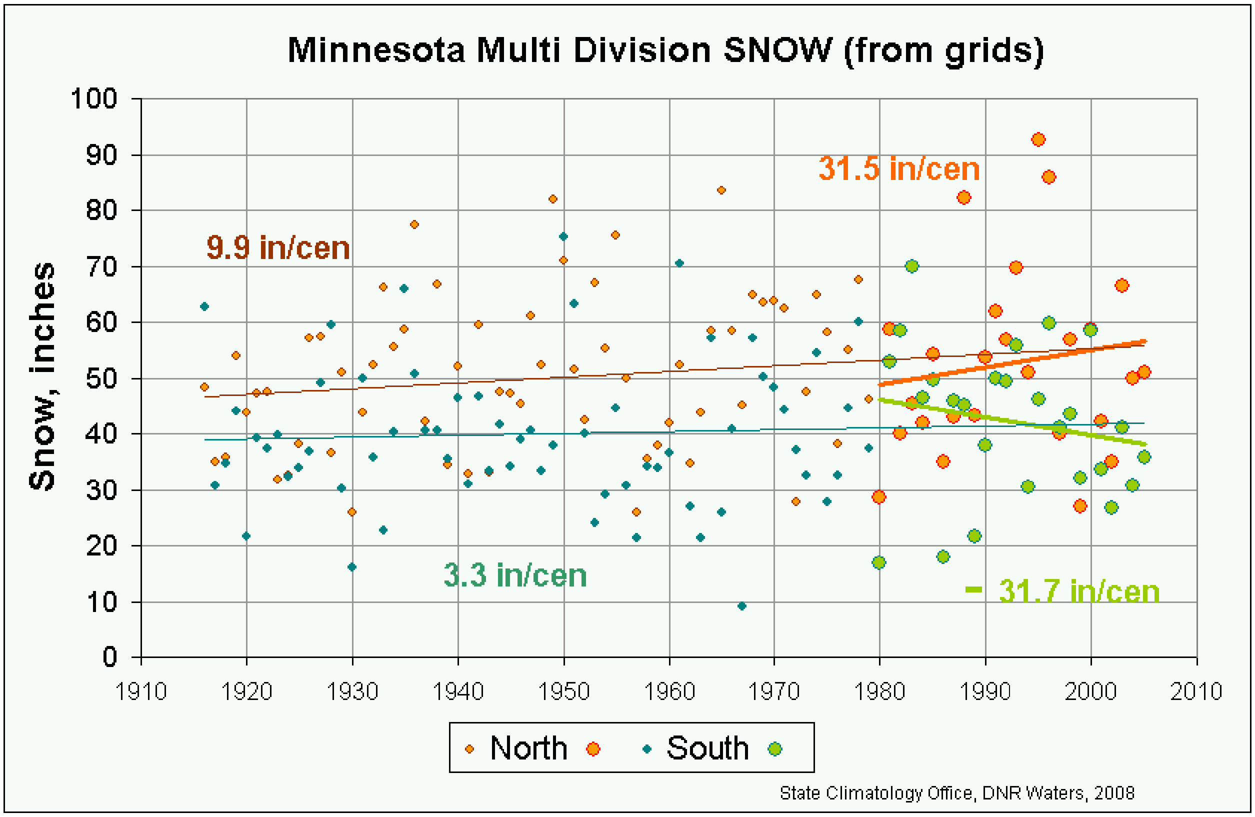


Figure 15. Long-term patterns of snowfall across Minnesota grouped by northern Minnesota climate zones (zones 1-3) and southern Minnesota climate zones (zones 7-9). Data are from the Minnesota State Climatology Office.

invasive plant in highly disturbed systems may not outweigh losses to clean water and habitat for fish and waterfowl that result from the removal.

Continued monitoring and potential research questions to address. The Sentinel Lakes network was established in 2008. Since that time routine monitoring of water quality, plankton, fish and plant composition, water level and physical measurements, and a variety of ancillary data have been compiled for the 24 lakes. Special studies were undertaken on several deep lakes that support cold and cool water fisheries using Environment Natural Resources Trust Fund dollars. To date, excellent baseline data has been established for the 24 lakes. Continued monitoring of the 24 lakes is essential to reduce uncertainty and improve understanding of how major drivers of change such as development, agriculture, climate change, and invasive species can affect water quality, lake habitats and fish populations.

The sentinel lakes provide a good reference for examining specific lake management issues and developing management recommendations. In this report, the affect of curly-leaf on water quality and temporal trends in curly-leaf growth have been examined across several lakes. Recommended monitoring and research that would further advance and test findings in this report include:

1. Annual spring curly-leaf plant surveys should be continued in the 11 lakes that have curly-leaf, if not expanded to the other three lakes where the plant is present. These surveys should be complemented by summer vegetation surveys. The surveys should also directly map spring surface coverage of curly-leaf pondweed.
2. Water temperature has a significant effect on curly-leaf growth rates, senescence and turion production. Dataloggers should continue to be used to record temperature in the 11 lakes.
3. Where possible, it would be good to document the progression of senescence of curly-leaf in these lakes. This information, would aid in interpreting the relative role of temperature on senescence as well as the role of senescence on water quality impacts (e.g., algal blooms and reduced transparency). In instances where MDNR or MPCA staff are unable to provide this documentation, one option may be to request sentinel lake volunteers make observations on the timing and progression of senescence as a part of their regular Secchi and profile monitoring events.
4. Water quality should be monitored at a minimum seasonally in all Sentinel lakes. Consistent with MPCA's watershed schedule, lakes with curly-leaf should be monitored for at least one and if possible two consecutive summers when their watershed is scheduled for monitoring in the ten-year rotation.
5. Sentinel lake volunteer observations should be maintained on all 11 lakes. If funding and opportunity exist, consider incorporating volunteer collection of TP and Chl-a at consistent sites in as many of the 11 lakes as possible to supplement ongoing agency monitoring.
6. Lake level monitoring should continue on all lakes where there currently are measurements being taken and new volunteers should be sought for lakes where measurements are not currently being taken.
7. A more comprehensive analysis of the response of biota to curly-leaf infestation should be conducted. This should include, but not limited to, zooplankton, phytoplankton, and fishery composition. A more detailed look at response of native vegetation and the moderating affect native vegetation has on curly-leaf may be merited as well.
8. Controlled studies in well-defined sites (e.g. mesocosms) within one or more sentinel lakes could allow for improved qualitative and quantitative assessment of CLP response to snow cover.
9. The impact of curly-leaf senescence on lake water quality should be quantified. This could involve development of limnological models in various lake types to quantify thresholds (if any) of curly-leaf pondweed abundance on water quality and relative contribution to nutrient loading.

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