Variations in shoreline vegetation and turbidity of shallow lakes.

Ryan D. Sullivan[1], La Toya Kissoon [2], Donna Jacob[1], Mark Hanson[3], Emily K Fischbach[1], and Marinus Otte[1]

[1] Wet Ecosystem Research Group, Department of Biological Sciences, North Dakota State University, Fargo, ND.
[2] Wet Ecosystem Research Group, Department of Biological Sciences, North Dakota State University, Fargo, ND. Corresponding Author: latoya.kissoon@gmail.com Phone: 701-231-8999.
[3] Wetland Wildlife Population and Research Group, Minnesota Department of Natural Resources, Bemidji, MN.

Abstract
Shoreline vegetation provides vital ecological services and can impact water quality of shallow lakes. We determined the area and composition of shoreline vegetation for 20 shallow lakes of varying turbidities in the Prairie Parkland Province of Minnesota. We examined differences in shoreline vegetation between clear and turbid lakes and identified relationships between shoreline vegetation and several lake environmental variables (lake depth, submerged vegetation cover, turbidity, chlorophyll-a, total phosphorus, Ca+Mg, conductivity, and pH). In contrast to turbid lakes, the clear lakes had greater emergent and submerged vegetation cover. *Typha* spp. dominated the shorelines of clear lakes, while woody vegetation dominated the shorelines of the turbid lakes. Redundancy analysis (RDA) showed depth and chlorophyll-a concentrations were related to emergent vegetation composition. The percent shoreline of *Typha* spp. was negatively associated with chlorophyll-a concentrations and the percent shoreline of woody vegetation was positively associated with water depth.

Key words:
chlorophyll-a; emergent; shallow lakes; *Typha* spp.; turbidity.

Introduction
Aquatic plants play a crucial role in the function of shallow lakes that includes preventing the suspension of sediments and subsequent release of nutrients, uptake of nutrients that would otherwise be available for algal growth, and provision of food and habitat for fish, invertebrates, and water birds (Dieter 1990; Blindow 1992; Weisner et al. 1994; Scheffer 1999, 2004; Horppila and Nurminen 2001, 2005). Lake shorelines can be colonized by a variety of emergent plant species, which provide various ecological services for lakes

such as diminished runoff, nutrient sequestration (Tyler et al. 2012), wave attenuation, shoreline stability, and provision of food and habitat for fish, invertebrates, water birds and other wildlife (Cronk and Fennessey 2001; Scheffer 2004).

The plant communities associated with shallow lakes can vary as these lakes shift from a clear, plant-dominated regime to a turbid, phytoplankton-dominated regime and back again (Blindow et al. 1998; Scheffer and Jeppesen 1998; Bayley et al. 2007; Zimmer et al. 2009). Clear lakes generally have low phytoplankton biomass and abundant submerged vegetation (Bayley et al. 2003). Submerged plants help maintain a clear-water environment by reducing sediment resuspension, releasing allelopathic compounds that inhibit phytoplankton growth, providing habitat for algae grazing zooplankton, and sequestering nutrients making them unavailable to phytoplankton (Blindow 1992; Weisner et al. 1994).

Algal blooms form when environmental conditions favor excessive phytoplankton growth (Assmy and Smetacek 2009) and can occur naturally or as a result of nutrient loading from surface runoff of agricultural or nutrient-rich uplands (Welch et al. 1979; Nilsson and Håkanson 1992; Carstensen et al. 2007). Freshwater algal blooms 1) decrease the aesthetic and recreational value of water bodies by coating the water surface with a green scum and producing foul smells, 2) release toxins such as microcystins, anatoxins, and nodularins, and 3) dramatically alter photic zone depths, levels and distribution of available nutrients, and dissolved oxygen concentrations (Ridge et al. 1995; Anderson 2007; Lopez et al. 2008). Management of algal blooms in shallow lakes is becoming a high priority because of their increasing occurrence and negative effects (Arbuckle and Downing 2001; Fraterrigo and Downing 2008).

Preemptive methods of controlling algal blooms often focus on constructed wetlands to remove excess nutrients and contaminants in wastewater and agricultural runoff (Salt et al. 1995; Goulet and Pick 2001; Hoagland et al. 2001; O'Sullivan et al. 2004). Abundant emergent vegetation in constructed wetlands often decreases nutrient availability for phytoplankton by uptake and accumulation of nutrients, and by stabilizing sediment, thus decreasing resuspension of sediment-bound nutrients (Chen and Barko 1988; Hoagland et al. 2001; Horppila and Nurminen 2005). Emergent plants can also be a source of organic matter, which can bind nutrients and thus make them available for phytoplankton growth (Barnes 1980; Davies 1994; Jackson 1998; Goulet and Pick 2001). Organic matter accumulation enhances reducing conditions of wetland sediments and subsequently influences nutrient mobility (Golterman 1995; Jacob and Otte 2004a, 2004b). A variety of chemical and biological methods have been used to treat lakes where algal blooms are problematic (Lembi 2002). For example, the application of barley straw (*Hordeum vulgare*), is reported to produce algae-static effects upon decomposition, inhibiting the reproduction of various algal species (Ridge et al. 1995; Everall and Lees 1996, 1997; Ball et al. 2001; Ferrier et al. 2005). Some submerged plants such as e*ratophyllum demersum, Chara* spp., and *Stratiotes obliquus* may exert allelopathic effects on algal growth (Wium-Andersen et al. 1983; Mjelde and Faafeng 1997; Mulderij et al. 2005). Della Greca (1990) reported that *Typha latifolia* produced allelopathic compounds that inhibited the growth of blue-green algae in cultures, but field studies have yet to confirm these findings. Here, we compared shallow lakes of varying turbidities to identify relationships between shoreline vegetation and the environmental variables at these sites. We considered the shoreline vegetation as the fringe or marginal emergent vegetation occurring from water depths of approximately 1 m to waterlogged soil on the shore (where water was not standing) (Sculthorpe 1967; Cronk and Fennessy 2001). We hypothesized that lakes with more shoreline vegetation, especially areas with dense *Typha* stands, would often be characterized by clear-water conditions in response to large litter inputs.

Methods

Vegetation assessment

Our study was carried out on 20 shallow lakes in southwestern Minnesota in the Prairie Parkland Ecological Province (Omernik 1987) during August 8-18, 2011 (Figure 1). More than 80% of the land in these watersheds is agricultural (Minnesota Geospatial Information Office Staff 1999). For each lake, the percent shoreline vegetation was determined at 10 locations around the lake. Each of the 10 sampling locations was located more or less equidistant of one another and at least 4 m from shoreline. At each location, we identified the plant species present and the percent cover of each species over an approximately 50 m transect that was parallel to the shoreline. Species were identified on site or collected for identification in the laboratory. Vegetation was grouped into the following 7 categories: *Typha* spp. (hereafter *Typha*), *Scirpus* spp. (hereafter *Scirpus*), *Phalaris arundinacea* (hereafter *Phalaris*), *Polygonum amphibium*, *Sparganium* spp., *Asclepias incarnata* and woody (including all mature trees). *Polygonum amphibium*, *Sparganium* spp., and *Asclepias incarnata* occurred in less than 15% of the lakes and so were not included in the analysis. Total emergent vegetation area (EVA) and basin area (BSN) for each lake were estimated using aerial photographs (details described by Hanson et al. 2012; Table 1). Woody shoreline (trees, shrubs) vegetation was not included in this delineation because it was not classified as emergent vegetation. The percent cover of submerged aquatic vegetation (SAV) was also determined at each of the 10 locations using an acrylic glass bottom cylinder (Kissoon et al. 2013).

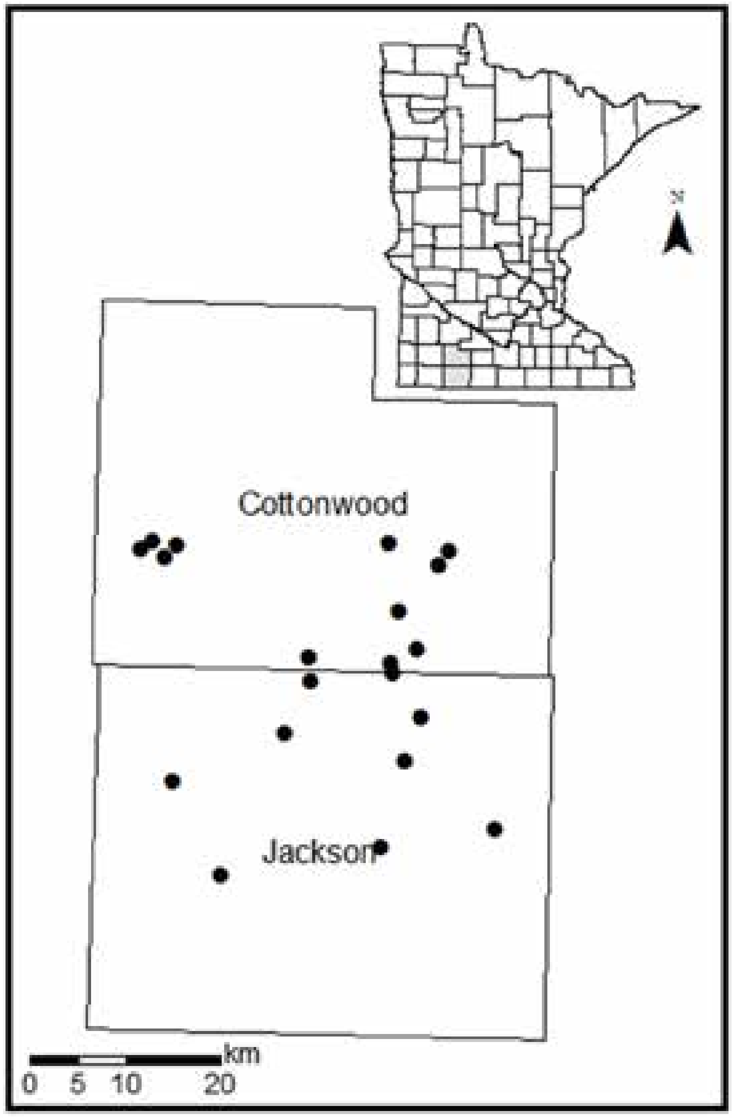

Figure 1: Map of study area showing the locations of the 20 shallow lakes in southwestern Minnesota that were used in this study.

Water sampling and analysis

Water samples were collected at approximately the same 10 locations at depths of 25 cm and a portion of the water sample was used to measure turbidity using a Hach® Portable Turbidimeter (Model 2100P) and pH using a VWR Symphony SP90M5 Handheld Multi-meter. The remaining water was filtered (0.45-μm pressure filter, Pall Corporation Supor® -450), acidified with 0.1 ml HNO_3, and later analyzed for Ca and Mg with a Spectro Genesis Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). The sum of the mmol l^{-1} f Ca and Mg (Ca+Mg) was used as an indicator of alkalinity (Kissoon et al. 2013). Conductivity, chlorophyll-*a* (chl-a), and total phosphorus concentrations (TP) were measured in water samples collected from two different locations in each lake during July of the same year. Chl-a was determined using fluorometry following acetone extraction and TP was measured according to methods of APHA (1994).

Regime	Lake ID	Emergent Vegetation Area (EVA)	Basin Area	EVA/Basin Area
		hectares	*hectares*	*ratio*
Turbid	03	0.23	40.61	0.01
	04	0.00	42.31	0.00
	06	2.27	6.14	0.37
	07	19.94	38.33	0.52
	08	0.33	6.52	0.05
	09	0.15	26.24	0.01
	11	0.97	12.45	0.08
	12	1.19	4025	0.03
	16	2.50	37.48	0.07
	19	0.36	13.93	0.03
	20	2.00	31.75	0.06
Clear	01	15.87	40.41	0.39
	05	2.05	26.75	0.08
	10	10.20	13.49	0.76
	13	8.65	11.54	0.75
	14	23.47	31.58	0.74
	15	2.27	58.66	0.04
	17	0.66	3.49	0.19
	18	1.09	3.81	0.29
	21	1.54	3.59	0.43

Table 1: Emergent vegetation area and emergent vegetation area relative to basin area for 20 shallow lakes in Minnesota (*Lake 04 had a predominant woody shoreline, which was not included in the delineation of emergent vegetation).

Statistical analysis

Prior to performing statistical analyses, turbidity, chl-a, Ca+Mg, and macrophyte data were log transformed to increase homogeneity of variance. K-means cluster analysis (Lattin et al. 2003) was carried out in Minitab to classify lakes into two groups based on, turbidity, chl-a concentrations, and submerged vegetation cover. The two resulting groups consisted of lakes in clear (macrophyte-dominated) and turbid regimes. A General Linear Model was then used to test for significant differences between the clear and turbid lakes (One-Way ANOVA, $p<0.05$) using Minitab® Minitab® 15 © 2006 Minitab Inc.). Pearson correlations and p-values were calculated in Minitab to explore the relationships between the percent shoreline for the different vegetation categories, emergent vegetation area relative to basin size, and turbidity. Relationships between environmental variables (depth, SAV cover, turbidity, chl-a, pH, Ca+Mg, conductivity, and total phosphorus) and percent shoreline vegetation were assessed using redundancy analysis (RDA) in CANOCO (© 2005 CANOCO Version 4.5). Preliminary Detrended Correspondence Analysis (DCA) indicated that linear gradient analysis (RDA) was appropriate because the gradient lengths were < 4.0 standard deviations (ter Braak and Šmilauer 2002). Prior to performing the RDA the shoreline vegetation data were relativized by maxima to reduce the influence of highly abundant species (McCune and Grace 2002) and the environmental variables were log transformed to increase homogeneity of variance. Forward selection with Monte Carlo permutation tests (999 permutations) was used to identify environmental variables associated with variation in shoreline vegetation for inclusion in the final model ($p<0.05$).

Results

Clear lakes had larger areas of emergent vegetation and higher ratios of emergent vegetation: basin area (Table 2). *Typha* was the most abundant shoreline vegetation in clear lakes while woody vegetation was more abundant in the margins of turbid lakes (Figure 2). The percent shoreline extent of *Phalaris* and *Scirpus* did not differ between the turbid and clear lakes. Depth, turbidity, and chl-a concentrations were greater in turbid lakes, while submerged vegetation was more abundant in the clear lakes (Table 2). Total phosphorus, conductivity, Ca+Mg concentrations, and pH did not differ between turbid and clear lakes.

The extent (percent) of shoreline for the different vegetation categories correlated with several environmental variables. For example, *Phalaris* was positively correlated with chl-a and total phosphorus, while *Typha* was negatively correlated with depth, turbidity, and chl-a and positively correlated with SAV cover. Woody vegetation was positively correlated with depth, turbidity, and chl-a and negatively correlated with SAV cover. Emergent vegetation area was negatively correlated with depth, turbidity, and pH, but positively correlated with SAV cover and Ca+Mg. The ratio of emergent vegetation area: basin area was negatively correlated with depth, turbidity, chl-a, and pH and positively correlated with SAV cover and Ca+Mg. Results of the RDA indicated that water depth and chl-a were associated with 45% of the variance in percent of shoreline vegetation. Percent shoreline of *Typha* was negatively associated with chl-a while woody vegetation and *Scirpus* were positively associated with water depth (Figure 3).

Discussion

Our study found that the shorelines of clear shallow lakes in Minnesota's prairie parkland region had more extensive emergent vegetation compared to turbid lakes, and that these stands of vegetation tend to be dominated by *Typha*. Previous studies indicated that emergent vegetation accumulates elements in the rhizosphere and plant tissues (Kissoon et al. 2010, 2011) and sequesters nutrients (Tyler et al. 2012), demonstrating their potential to decrease nutrient availability and perhaps turbidity in shallow lakes. Dense stands of *Typha* may

Variables	Clear (n=9)	Turbid (n=11)
Emergent vegetation area (hectares)	7.3±7.6*	2.7±5.6
Emergent vegetation area/basin area (ratio)	0.4±0.3*	0.1±0.2
Environmental variables		
Depth (m)	0.9±0.4	1.5±0.7*
Turbidity (NTU)	8±8	45±25*
chlorophyll-a ($\mu g\ l^{-1}$)	35±46	105±97*
SAV cover (%)	88±29*	14±33
pH	8.9±0.7	9.0±0.3
Ca+Mg (mmol l^{-1})	2.5±0.6	2.2±0.4
Conductivity (µS)	351±75	381±49
Total phosphorus ($\mu g\ l^{-1}$)	147±146	195±98

Table 2: Mean emergent vegetation area and environmental variables (*indicates the significantly higher value between lakes for a particular variable; p≤0.01).

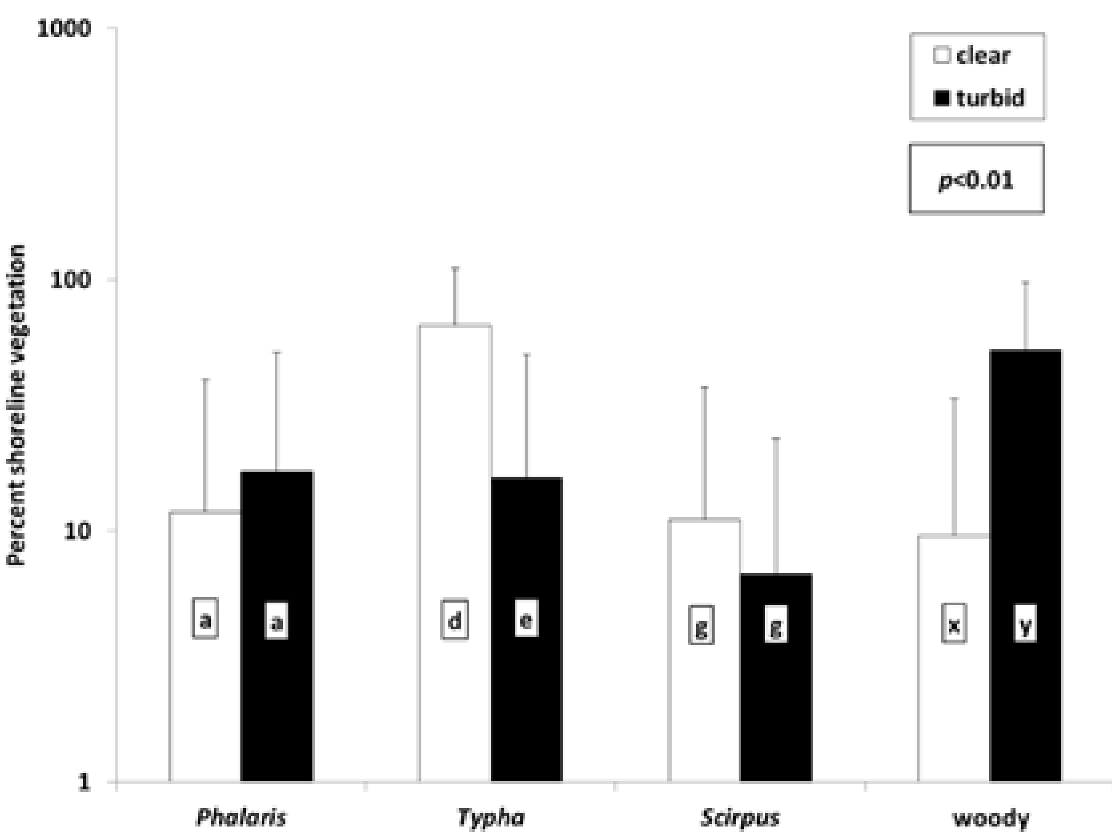

Figure 2: Mean percent of shoreline vegetation for the four different vegetation categories (*Phalaris* spp., *Typha* spp., *Scirpus* spp., woody) for clear and turbid lakes (different letters within each vegetation category indicate significant differences between turbid (n=8) and clear (n=12) lakes, p<0.01)

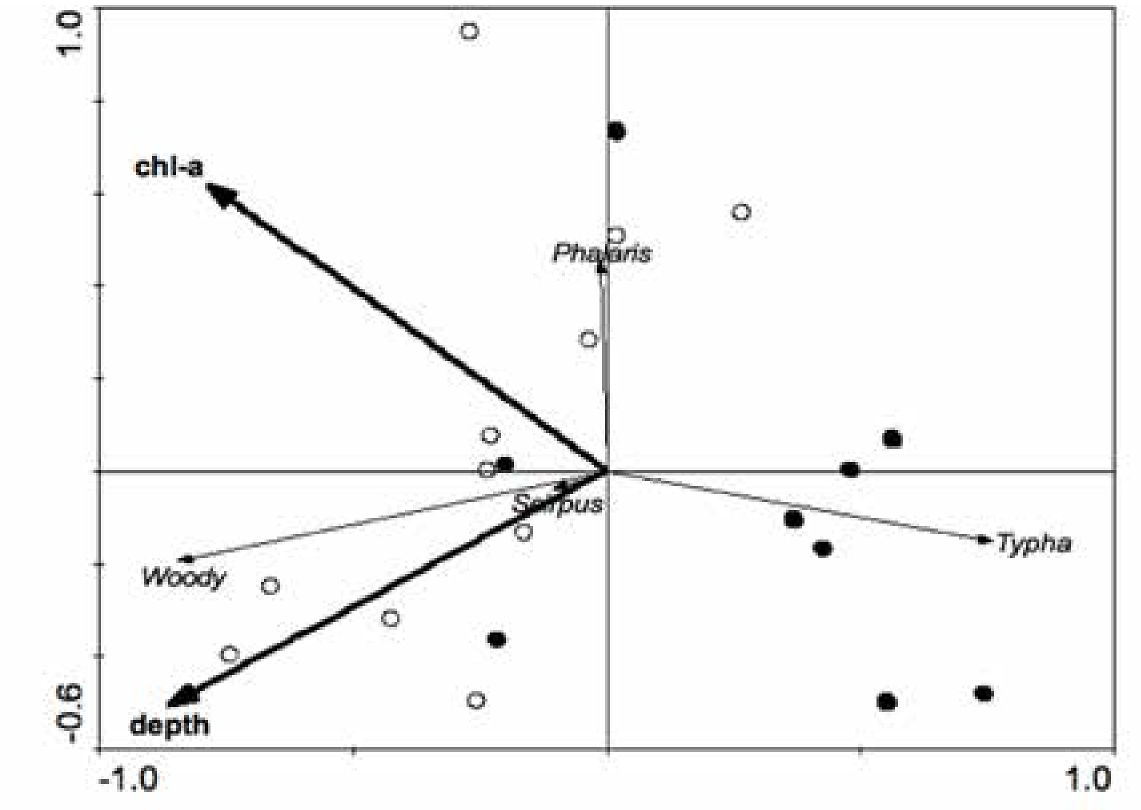

Figure 3: RDA ordination plot of percent shoreline vegetation constrained by environmental variables (environmental variables (in bold): depth and chlorophyll-*a* concentrations (chl-a); vegetation categories (occurred in >14% of lakes): *Typha* spp., *Scirpus* spp., *Phalaris* arundinacea and woody vegetation; Lake regimes: turbid (O), clear (•)).

decrease and block nutrient access to algae due to *Typha's* affinity for nitrogen and phosphorus (Koottatep and Polprasert 1997; Chiang et al. 2000; Maddison et al. 2009). Dubbe et al. (1988) reported that nutrient utilization by *Typha* peaks during June to August, potentially taking up these nutrients when phytoplankton populations are most dependent on them. The greater emergent vegetation area in the clear lakes also allow sediment to stabilize (Dieter 1990) and may serve to filter nutrient runoff, perhaps limiting nutrient inputs to open-water areas in shallow lakes (Horppila and Nurminen 2001; Tyler et al. 2012).

Emergent vegetation area may also contribute to clear water conditions by providing habitat for aquatic invertebrates that feed on algae (Voigts 1976; Campeau et al. 1994; Oertli and Lachavanne 1995; Lembi 2003). Emergent plants and resulting litter may also protect invertebrate populations by providing them with cover from predators (Campeau et al. 1994). Low oxygen levels in *Typha* stands also discourage fish and invertebrates that may prey on zooplankton, thus favoring higher zooplankton densities which, in turn, contribute to lower phytoplankton biomass and clear-water conditions (Timms and Moss 1984; Murkin et al. 1992; Scheffer 2004). The clear lakes were also dominated by SAV that could also be contributing to the clear conditions by stabilizing sediment, blocking nutrient access to algae, and providing suitable habitat to algal grazers (Scheffer and Jeppesen 1998; Scheffer 2004).

	Phalaris	*Thypha*	woody	EVA	EVA: Basin area
Depth		-0.482	0.755	-0.505	-0.618
Turbidity		-0.433	0.359	-0.341	-0.478
Chl-a	0.411	-0.493	0.624		-0.545
Sav cover		0.532	-0.492	0.346	0.583
Ca+Mg				0.361	0.386
pH				-0.328	-0.358
Total Phosphorus	0.477				

Table 3: Pearson correlations for shoreline vegetation and environmental variables (only significant correlations where $r \geq 0.316$ and $p<0.01$ are shown).

Allelopathic substances released by submerged vegetation may also decrease phytoplankton growth and contribute to the clear-water conditions (Wium-Andersen et al. 1983; Mjelde and Faafeng 1997). Della Greca et al. (1990) isolated an allelopathic compound from *Typha latifolia*, which inhibited blue-green algae in cultures. This allelopathic compound may be released from *Typha* stands and might favor clear-water conditions in lakes with *Typha*-dominated shorelines. Ridge et al. (1995, 1999) reported algae-static properties associated with brown-rotting wood and with the breakdown of tannins in oak leaf litter. However, in our study, the lake shorelines dominated by woody vegetation tended to be turbid and supported high phytoplankton biomass.

The results of the RDA indicated that water depth and chl-a were important variables associated with the extent of shoreline emergent vegetation. Water levels play a key role in the distribution of emergent vegetation (Squires and van der Valk 1992; Grosshans and Kenkel 1997) and may explain the variation in the composition and abundance of emergent vegetation in our shallow lakes. Negative correlations between emergent vegetation area and water depth also indicated that water levels play a critical role in the abundance of emergent plants along the margins of shallow lakes. Negative relationships between turbidity and chl-a with emergent vegetation area and extent of *Typha* may indicate the role of emergent vegetation in maintaining clear-water conditions by stabilizing sediments and subsequently contributing to decreased nutrient availability and phytoplankton growth (Dieter 1990).

Initially we suspected litter inputs from decomposing emergent vegetation in our shallow lakes inhibited the reproduction of phytoplankton, similar to responses observed following additions of barley straw. The lignin content of emergent vegetation such as *Typha* is about 15% and similar to that seen in barely straw (Ridge et al. 1995; Jaques and Pinto 1997). Barley straw has been reported to have algae-static effects which result from the decomposition of its ligneous fraction (Ridge et al. 1995, 1999; Everall and Lees 1996, 1997; Ball et al. 2001; Ferrier et al. 2005). In fact, we found that the extent of emergent vegetation area and presence of a *Typha*-dominated shoreline were positively associated with clear lakes. Water depth appeared to play a role in the emergent vegetation composition and possibly contributed to water clarity. Other factors such as submerged vegetation cover and nutrient availability may also explain clear or turbid conditions in these lakes. Future studies are needed to determine whether *Typha* and other emergent vegetation inhibit phytoplankton growth, and if so, in what ways. We hypothesize that *Typha* litter inputs may reduce phytoplankton growth rates in shallow lakes similar to additions of barley straw and, if so, addition of a *Typha* litter or extract to lakes may warrant evaluation as a management option for future control of phytoplankton in shallow or eutrophic lakes.

Conclusion

Shallow lakes with a greater area of emergent vegetation and a Typha-dominated shoreline tend to be clear. Depth and water clarity appear to be related to the emergent vegetation composition. There may be several benefits of the extent of the emergent vegetation area and a Typha-dominated shoreline that contribute to low lake turbidity. Some of these include the capacity of emergent plants to take up nutrients otherwise available for algae, provide refugia for algae grazing invertebrates, and contribute organic matter that bind nutrients. Future studies are needed to determine if algae-static compounds are released from emergent vegetation litter in field conditions.

Acknowledgements

This publication was made possible by ND ESPCoR and NSF (grant #EPS-0814442), the Minnesota Department of Natural Resources (The Legislative-Citizen's Commission on Minnesota Resources), The Wetland Foundation, Sigma Xi Grants-in-Aid of Research, and by NIH grant number P20 RR016471 from the INBRE program of the National Institute of General Medical Sciences. We would also like to thank Dr. Wei Lin of North Dakota State University for the use of his turbidimeter. Thanks to Alex Yellick for constructing a map of the study area.

References

Anderson DM (2007) The ecology and oceanography of harmful algal blooms: multidisciplinary approaches to research and management. IOC Technical Series 74, UNESCO 2007. http://unesdoc.unesco.org/images/0016/001631/163114e.pdf Accessed 25 February 2013

APHA (1994) Standards methods for the examination of water and wastewater. American Public Health Association, Washington D.C.

Arbuckle KE, Downing JA (2001) The influence of watershed land use on lake N:P in a predominantly agricultural landscape. Limnol Oceanogr 46:970-975.

Assmy P, Smetacek V (2009) Algal Blooms. In: Schaechter M (ed) Encyclopedia of microbiology, 3rd edn. Elsevier, Oxford, pp 27-41.

Ball AS, Williams M, Vincent D, Robinson J (2001) Algal growth control by a barley straw extract. Bioresour Technol 77:177-181.

Barnes RSK (1980) The Unity and diversity of aquatic ecosystems. In: Barnes RSK, Mann KH (eds) The Fundamentals of Aquatic Ecosystems. Blackwell Scientific Publications, Oxford. pp. 5-23.

Campeau S, Murkin HR, Titman RD (1994) Relative importance of algae and emergent plant litter to freshwater marsh invertebrates. Can J Fish Aquat Sci 51:681-692.

Carstensen J, Henriksen P, Heiskanen A-S (2007) Summer algal blooms in shallow estuaries: definition, mechanisms, and link to eutrophication. Limnol Oceanogr 52:370-384.

Chen RL, Barko JW (1988) Effects of freshwater macrophytes on sediment chemistry. J Freshw Ecol 4:279-289.

Chiang C, Cract CB, Rogers DW, Richardson CJ (2000) Effects of 4 years of nitrogen and phosphorus additions on Everglades plant communities. Aquat Bot 68:61-78.

Cronk JK, Fennessy MS (2001) Wetland plants: biology and ecology. Lewis Publishers, Boca Raton, FL.

Davies BE (1994) Soil chemistry and bioavailability with special reference to trace elements. In: Farago M (ed) Plants and the chemical elements: biochemistry, uptake, tolerance and toxicity. VCH Verlagsgesellschaft, Weinheim, Germany, pp. 2-30.

Della Greca M, Mangoni L, Molinaro A, Monaco P, Previtera L (1990) (20S)-4α-Methyl-24-Methylenecholest-7en-3β-ol, an allelopathic sterol from *Typha latifolia*. Phytochem 29:1797-1798.

Dieter CD (1990) The importance of emergent vegetation in reducing sediment resuspension in wetlands. J Freshw Ecol 5:467-473.

Dubbe DR, Garver EG, Pratt DC (1988) Production of cattail (*Typha* spp.) biomass in Minnesota, USA. Biomass 17:79-104.

Everall NC, Lees DR (1996) The use of barley straw to control general and blue-green algal growth in a Derbyshire reservoir. Water Res 30:269-276.

Everall NC, Lees DR (1997) The identification and significance of chemicals released from decomposing barley straw during reservoir algal control. Water Res 31:614-620.

Ferrier MD, Butler BR Sr, Terlizzi DE, Lacouture RV (2005) The effects of barley straw (Hordeum vulgare) on the growth of freshwater algae. Bioresource Technol 96:1788-1795.

Fraterrigo JM, Downing JA (2008) The influence of land use on lake nutrients varies with watershed capacity. Ecosystems 11: 1021-1034.

Golterman HL (1995) The labyrinth of nutrient cycles and buffers in wetlands: results based on research in the Camargue (southern France). Hydrobiol 315:39-58.

Goulet RR, Pick FR (2001) The effects of cattails (*Typha latifolia* L.) on concentrations and partitioning of metals in surficial sediments of surface-flow constructed wetlands. Water Air Soil Pollut 132:275-291.

Grosshans RE, Kenkel NC (1997) Dynamics of emergent vegetation along natural gradients of water depth and salinity in a prairie marsh: delayed influences of competition. UFS (Delta Marsh) Annual Report 32: 83-93.

Hanson MA, Herwig BR, Zimmer KD, Fieberg J, Vaughn SR, Wright RG, Younk JA (2012) Comparing effects of lake-and watershed-scale influences on communities of aquatic invertebrates in shallow lakes. PLOS ONE 7: e44644.

Hoagland CR, Gentry LE, David MB (2001) Plant nutrient uptake and biomass accumulation in a constructed wetland. J Freshw Ecol 16:527-540.

Horppila J, Nurminen L (2001) The effect of an emergent macrophyte (T*ypha angustifolia*) on sediment resuspension in a shallow north temperate lake. Freshw Biol 46:1447-1455.

Horppila J, Nurminen L (2005) Effects of different macrophyte growth forms on sediment and P resuspension in a shallow lake. Hydrobiol 545:167-175.

Jackson LJ (1998) Paradigms of metal accumulation in rooted aquatic vascular plants. Sci Total Environ 219:223-231.

Jacob DL, Otte ML (2004a) Long-term effects of submergence on metals in a 90-year old abandoned Pb-Zn tailings pond. Environ Pollut 130: 337-345.

Jacob DL, Otte ML (2004b) Influence of *Typha latifolia* and fertilization on metal mobility in two different Pb-Zn mine tailings types. Sci Total Environ 333: 9-24.

Jaques N, Pinto P (1997) Seasonal differences in the decomposition of *Typha angustifolia* leaves in a Mediterranean river. Limnetica 13:19-23.

Kissoon LT, Jacob DL, Otte ML (2010) Multi-Element accumulation near Rumex crispus roots under wetland and dryland conditions. Environ Pollut 158: 1834-1841.

Kissoon LT, Jacob DL, Otte ML (2011) Multiple elements in *Typha angustifolia* rhizosphere and plants: Wetland versus dryland. Environ Exp Bot 72: 232-241.

Kissoon LT, Jacob DL, Hanson MA, Herwig BR, Bowe SE, Otte ML (2013) Macrophytes in shallow lakes: relationships with water, sediment and watershed characteristics. Aquatic Botany, 109, 39-48.

Koottatep T, Polprasert C (1997) Role of plant uptake on nitrogen removal in constructed wetlands located in the tropics. Water Sci Technol 36:1-8.

Lembi CA (2002) Aquatic Plant Management: Barley straw for algae control. Purdue University, West Lafayette, IN. http://www.btny.purdue.edu/pubs/APM/APM-1-W.pdf Accessed 25 February 2013.

Lembi CA (2003) Control of nuisance algae. In: Wehr JD, Sheath RG (eds) Freshwater algae of North America: ecology and classification. Academic Press, Boston, pp 805-834

Lopez CB, Jewett EB, Dortch Q, Walton BT, Hudnell HK (2008) Scientific Assessment of Freshwater Harmful Algal Blooms. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, DC. http://www.cop.noaa.gov/stressors/extremeevents/hab/habhrca/FreshwaterReport_final_2008.pdf Accessed 25 February 2013.

Maddison M, Soosaar K, Mauring T, Mander U (2009) The biomass and nutrient and heavy metal content of cattails and reeds in wastewater treatment wetlands for the production of construction material in Estonia. Desalination 246:120-128.

McCune B, Grace JB (2002) Analysis of Ecological Communities. MjM Software Design, Gleneden Beach, OR.

Minnesota Geospatial Information Office Staff (1999) Minnesota Land Use and Cover: 1990s Census of the Land. Minnesota Geospatial Information Office, St. Paul, MN. http://www.mngeo.state.mn.us/landuse/ Accessed 25 February 2013.

Mjelde M, Faafeng BA (1997) *Ceratophyllum demersum* hampers phytoplankton development in small Norwegian lakes over a wide range of phosphorus concentrations and geographical latitude. Freshw Biol 37: 355-365.

Mulderij G, Mooij WM, van Donk E (2005) Allelopathic growth inhibition and colony formation of the green alga *Scenedesmus obliquus* by the aquatic macrophyte Stratiotes aloides. Aquat Ecol 39: 11-21.

Murkin EJ, Murkin HR, Titman RD (1992) Nektonic invertebrate abundance and distribution at the emergent vegetation-open water interface in the delta-marsh, Manitoba, Canada. Wetlands 12: 45-52.

Nilsson A, Håkanson L (1992) Relationships between drainage area characteristics and lake water quality. Environ Geol Water Sci 19: 75-81.

O'Sullivan AD, Moran BM, Otte ML (2004) Accumulation and fate of contaminants (Zn, Pb, Fe and S) in substrates of wetlands constructed for treating mine wastewater. Water Air Soil Pollut 157: 345-364.

Oertli B, Lachavanne JB (1995) The effects of shoot age on colonization of an emergent macrophyte (Typha latifolia) by macroinvertebrates. Freshw Biol 34: 421-431.

Omernik JM (1987) Ecoregions of the conterminous United States. Ann Assoc Am Geogr 77: 118-125.

Ridge I, Pillinger J, Walters J (1995) Alleviating the problems of excessive algal growth. In: Harper DM, Ferguson ADJ (eds) The Ecological Basis for River Management. Wiley, England, pp 211-218.

Ridge I, Walters J, Street M (1999) Algal growth control by terrestrial leaf litter: a realistic tool? Hydrobiol 395/396:173-180.

Salt DE, Blaylock M, Kumar NPBA, Dushenkov V, Ensley BD, Chet I (1995) Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. Biotechnology 13: 468-474.

Scheffer M (1999) The effect of aquatic vegetation on turbidity; how important are the filter feeders? Hydrobiologia 408/409: 307-316.

Scheffer M (2004) Ecology of Shallow Lakes. In: Usher MB, DeAngelis DL, Manly BFJ (eds), Population and Community Biology Series 202. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Sculthorpe CD (1967) The biology of aquatic vascular plants. Edward Arnold Publishers Ltd., London.

Squires L, van der Valk AG (1992) Water-depth tolerances of the dominant emergent macrophytes of the Delta Marsh, Manitoba. Can J Bot 70: 1860-1867.

ter Braak CJF, Šmilauer P (2002) Canoco Reference Manual and CanoDraw for Windows User's Guide. Biometris, Wageningen University and Research Center, Wageningen, The Netherlands.

Timms RM, Moss B (1984) Prevention of growth of potentially dense phytoplankton populations by zooplankton grazing, in the presence of zooplanktivorous fish, in a shallow wetland ecosystem. Limnol Oceanogr 19:472-486.

Tyler HL, Moore MT, Locke MA (2012) Potential for phosphate mitigation from agricultural runoff by three aquatic macrophytes. Water Air Soil Pollut 223: 4557-4564.

Voigts D (1976) Aquatic invertebrate abundance in relation to changing marsh vegetation. Am Midl Nat 95:313-322.

Welch EB, Perkins MA, Lynch D, Hufschimdt P (1979) Internal phosphorus related to rooted macrophytes in a shallow lake. In: Breck JE, Prentki RT, Loucks OL (eds) Aquatic plants, lake management, and ecosystem consequences of lake harvesting. Proceedings of Conference at Madison, Wisconsin, pp. 81-99.

Wium-Andersen S, Anthon U, Christophersen C, Houen G (1983) Allelopathic effects on phytoplankton by substances isolated from aquatic macrophytes (Charales). Oikos 39: 187-190.