Journal of the Minnesota Academy of Science

Volume 59 | Number 4 Article 2

1995

# Influence of Vegetated Wetlands on the Water Quality of Two Glacial Prairie Lakes

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## Abstract

We investigated the influence of vegetated wetlands on water quality of two eastern South Dakota glacial prairie lakes. Surface water from a 5,880 ha pastured basin drains into a 90 ha upstream Typha wetland and enters Lake Enemy Swim passing 400 m through Typha–Scirpus littoral wetland. A second 1,290 ha basin characterized by row crops and pasture drains into a 260 ha open water slough entering L. Enemy Swim adjacent to Typha–Scirpus littoral wetland. Water enters Lake Cochrane from two smaller drainage basins. Water from a 180 ha basin consisting of a pasture and wet meadow enters the lake after passing about 100 m through Typha–Scirpus littoral wetland. A second basin consisting of 120 ha of mixed row crops, pasture and wetlands drains into an open water sediment retention pond and enters L. Cochrane after passing 50 m through Typha–Scirpus littoral wetland.

At each lake, we measured water quality parameters in upstream drainages, in littoral wetlands, and at midlake sites in 1992 and 1993. In both lakes all forms of N were lesser and Fe were greater in concentration than all other sites in the drainages from upstream vegetated areas. Both N and P concentrations were greatest in the drainages from upstream open water areas resulting in small Si:P and Si:N ratios, and large N:Fe ratios. Concentrations of N and P decreased and Si:P and Si:N ratios increased passing through vegetated littoral wetlands, thus decreasing the likelihood of triggering phytoplankton shifts from desirable diatoms to undesirable bluegreen algal blooms.


## Introduction

A major water quality problem degrading the recreational use of prairie lakes is the formation of bluegreen algal blooms. Prairie lakes are usually too shallow to develop summer temperature stratification and nutrients recirculate continually. The importance of chemical nutrients in stimulating nuisance bluegreen algal blooms has been extensively studied in prairie lakes (1, 2).

Vegetated littoral zone wetlands may improve water quality by removing nitrogen (N) and phosphorus (P) from inflowing waters (3, 4). Uptake by rooted vegetation (5) and diatom periphyton (6) may contribute to this removal. Microbial action also concentrates N and P in macrophyte detritus with time (7). Sediment deposition also contributes to removal of incoming nutrients (8). Nitrogen may be removed by denitrification at the sediment interface (9) and volatilization of ammonia when pH > 7 (10). Emergence of many aquatic insects that spend their larval stages in the littoral zone may also remove nutrients (11). Mammals and migratory waterfowl may remove macrophyte biomass (12). Both upstream and adjacent littoral wetlands may remove nutrients from a lake (13).

Conversely, littoral zone vegetation may pull nutrients out of the sediments and release them to the water upon senescence (12). A review of 17 studies indicated N and P removal by wetlands in summer but less removal and some export in spring and particularly fall (3). Macrophyte herbivory by birds, mammals, fish and invertebrates may influence the timing and magnitude of nutrient release (12). Nutrient flow from the littoral zone to the limnetic zone may be facilitated by the movement of zooplankton and fish (14) and phytoplankton (6). In Lake Wingra, Prentki *et al.* (15) found the residence time of water in the littoral zone to be less than one–third day, facilitating planktonic transport of nutrients to the limnetic zone.

Littoral wetland–open water interactions are likely to be most important in smaller, vegetated lakes (16) and may be a dominant factor in the nutrient budget (12). Many prairie lakes are small and partially vegetated. However, studies of the impact of littoral wetlands on glacial prairie lakes are few. Studies on the influence of the littoral zone on concentrations of silica (Si) and iron (Fe) are also needed, as these nutrients may influence water quality of lakes by their influence on phytoplankton composition (17, 18). Littoral zone vascular plants concentrate Fe in their roots (19) but Fe may also be easily remobilized (20).


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Studies on the long term fate of metals removed in the littoral zone are lacking (4).

Measurements of nutrient concentrations both upstream from littoral zones and at the open water edge immediately downstream from the littoral zone document whether those littoral zones are acting as nutrient sources or sinks. Measurement in the central basins of lakes can estimate removal of nutrients by phytoplankton, a process that also occurs in littoral zone wetlands (6). Nutrient measurements need to be made during different precipitation regimes and on drainages from different landuse areas since nutrient concentrations are characteristically greater from croplands (21) and grazed pasture (22) than from ungrazed pasture or prairie. Since both vegetated wetlands (23) and open water sediment ponds (24) can remove incoming nutrients from water, effluents from both systems need to be compared.

The purpose of this study was to evaluate the influence of vegetated littoral zone wetlands on concentrations of potential algal nutrients, N, P, Si, and Fe in the water entering lakes. We compared nutrient concentrations of water entering the littoral zone wetlands with water within the littoral zone wetlands. We compared water entering the littoral zone from two upstream vegetated areas with water from two upstream open water wetlands. We also compared nutrient concentrations of water in littoral zone wetlands with the nutrient concentrations of water in midlake regions.

## Study Area

The lakes studied lie in glacial moraines of 12,000 to 14,000 years age in eastern South Dakota (26, 27). Lake Enemy Swim (Township 123 N, Ranges 53 and 54 W; Figure 1) has a surface area of 870 ha, mean depth of 4.8 m, maximal depth of 7.9 m, and drains a watershed of 9,030 ha. Lake Enemy Swim has a mean specific conductance of 489 *uS* $cm^{-2}$ with calcium ($Ca^{2+}$) and bicarbonate ($HCO_3^-$) the major ions (Table 1). It is moderately eutrophic (mean total P of 38 *ug* $L^{-1}$, Secchi depth of 1.8 m and chlorophyll *a* of 15 *ug* $L^{-1}$). Lake Enemy Swim is biologically diverse and has multiple basins with vegetated littoral zone wetlands. It presents the opportunity to measure upstream–downstream changes in concentrations of nutrients, as water flows from east to west through the lake basins.

The east drainage to L. Enemy Swim drains a large watershed of 5880 ha that is heavily grazed immediately upstream from a 90 ha *Typha* marsh. Downstream from the *Typha* marsh, the water travels about 400 m through a 20 ha *Typha–Scirpus* littoral wetland before entering the lake. The south drainage drains a cropped and grazed watershed of 1,290 ha, and flows through a 260 ha open water slough. It intermittently enters the lake through an open water channel adjacent to *Typha–Scirpus* littoral wetland. Water can flow either direction between L. Enemy Swim and the slough, depending on wind direction. Water can exit L. Enemy Swim through the slough to the south, or underground through collapsed outwash to the west.

**Table 1. Average concentrations of major ions (mg $L^{-1}$), temperature (°C) and wind stress (gm $cm^{-1}$ $sec^{-2}$) measured at in-lake sampling sites†.**

| Ion | Lake Enemy Swim | | | | Lake Cochrane | | | |
|---|---|---|---|---|---|---|---|---|
| | EL | EB | MB | SL | SL | WL | WB | EB |
| $Na^+$ | 7.5 | 8.0 | 8.0 | 8.0 | 105.5 | 105.5 | 106.0 | 108.0 |
| $K^+$ | 5.0 | 7.0 | 7.0 | 7.0 | 51 | 53 | 53 | 54 |
| $Mg^{2+}$ | 39.5 | 43.5 | 43.5 | 42.0 | 442 | 415 | 420 | 430 |
| $Ca^{2+}$ | 63.0 | 39.5 | 39.5 | 39.0 | 88.5 | 90.0 | 90.5 | 90.5 |
| $Si^-$ | 4.0 | 4.0 | 4.0 | 9.5 | 21.5 | 21.5 | 21.0 | 21.5 |
| $SO_4^{2-}$ | 23.5 | 26.5 | 26.5 | 27.0 | 1890 | 1900 | 1930 | 1910 |
| $HCO_3^-$ | 209 | 150 | 150 | 147 | 88 | 88 | 94 | 90 |
| $CO_3^{2-}$ | 84 | 84 | 88 | 84 | 160 | 160 | 160 | 160 |
| Temp | 17.9 | 16.7 | 17.0 | 20.8 | 18.5 | 19.0 | 17.7 | 17.4 |
| Wind | 0.20 | 0.25 | 0.23 | 0.03 | 0.07 | 0.08 | 0.09 | 0.10 |

† 12 observations per station for temperature, 6 for wind stress and 2 for major ions.

**Table 2. Macroscopic vegetation of the four littoral zones arranged in order of similarity index to the Enemy Swim east littoral zone (EL).**

| | Downstream from vegetated wetland | | Downstream from open water | |
|---|---|---|---|---|
| | **Enemy Swim EL** | **Cochrane SL** | **Cochrane WL** | **Enemy Swim SL** |
| *Chaetophora* sp. (alga) | + | | | |
| *Drepanocladus* sp. (moss) | + | | | |
| *Hippurus vulgaris* L. | + | | | |
| *Sium suave* Walt. | + | | | |
| *Eleocharis* sp. | + | | | |
| *Ceratophyllum demersum* L. | + | | | |
| *Utricularia vulgaris* L. | + | | | |
| *Zannichellia palustris* L. | + | | | |
| *Juncus balticus* Willd. | + | | | |
| *Sagittaria* sp. | + | | | |
| *Chara* sp. (alga) | + | + | + | |
| *Carex* sp. | + | + | + | |
| *Lemna trisulca* L. | + | + | + | |
| *Lemna turionifera* Landolt | + | + | + | |
| *Salix exigua* Nutt. | + | + | + | + |
| *Populus deltoides* Bartr. ex Marsh | + | + | + | + |
| *Typha* sp. | + | + | + | + |
| *Rhizoclonium* sp. (alga) | | + | + | + |
| *Phalaris arundinancea* L. | | + | + | + |
| *Myriophylium exalbescens* Fern. | | + | + | |
| *Fraxinus pennsylvanica* Marsh. | | | + | + |
| *Scirpus pungens* Vahl | | | + | |
| *Potamogeton pectinatus* L. | | | + | |
| *Phragmites australis* (Cav.) Trin. ex. Steud. | | | | + |
| *Polygonum coccineum* Muhl. ex Willd. | | | | + |

The L. Enemy Swim east littoral wetland was located on sand substrate, and had the greatest average wind stress of all four littoral zones sampled (Table 1). It had greater macrophyte species richness than the other three wetlands studied (Table 2). It had the greatest $Ca^{2+}$ and $HCO_3^-$ concentrations in L. Enemy Swim.

The vegetation of the L. Enemy Swim south littoral wetland was also on sand substrate. It had the least wind stress (Table 1) and plant diversity (Table 2) of the littoral zones. It had the greatest chloride ($Cl^-$) concentrations in L. Enemy Swim.

Lake Cochrane (Township 114 N, Range 47 W, Figure 2) has a surface area of 150 ha, mean depth of 3.9 m, maximal depth of 7.9 m and drains a small watershed of 360 ha. Lake Cochrane has no outlet and is subsaline with a mean specific conductance of 2,870 $uS\ cm^{-2}$ and magnesium ($Mg^{2+}$) and sulfate ($SO_4^{2-}$) are the major ions (Table 1). It is eutrophic (mean total P of 45 $ug\ L^{-1}$, Secchi depth of 1.3 m, and chlorophyll *a* of 23 $ug\ L^{-1}$). Lake Cochrane has a lower shoreline development index than L. Enemy Swim. The south inflow to L. Cochrane drains a watershed of 180 ha moderately grazed pasture and wet meadow, and enters the lake traveling about 100 m through a *Typha–Scirpus* littoral wetland. The west inflow to L. Cochrane drains a watershed of 120 ha of mixed row crops, grassland and wetlands. It flows into a constructed sediment retention pond. Outflow from the pond travels 50 m through *Typha–Scirpus* littoral wetland before entering the lake.

Both littoral wetlands in L. Cochrane were located in rich organic mud substrate. They were very similar to each other in wind stress and vegetation, and intermediate between the two littoral wetlands in L. Enemy Swim in those characteristics (Tables 1 and 2). The west littoral zone had greater macrophyte species richness and a beaver lodge was present in 1992. The upstream drainages were lower in conductivity than littoral and midlake stations in L. Cochrane.

## METHODS

Two vegetated littoral zone and two open water sites in each lake (Figures 1 and 2) were sampled 3 times between May 19 and August 31, 1992 and 3 times between May 2 and August 6, 1993. After the first sampling date, stations upstream from the littoral zone were sampled on all subsequent dates. Two samples were taken of each variable at each location. Total Kjeldahl N (TKN), nitrite- plus nitrate–N ($NO_2^-$ + $NO_3^-$-N), total P, Si, turbidity, pH, and chlorophyll *a* were measured at midlake and littoral zone sites on all dates in 1992 and at all stations in 1993. Iron was sampled on all but the first date. Secchi depth was measured at midlake stations on all dates. Temperature, electrical conductivity, and pH were measured at littoral zone and midlake stations. Wind velocity and direction were recorded at midlake and littoral zone stations and the direction of flow was noted at upstream locations on each date. Replicate samples for major ions ($Ca^{2+}$, $Mg^{2+}$, potassium [$K^+$], sodium [$Na^+$], $HCO_3^-$, carbonate [$CO_3^{2-}$], $Cl^-$ and $SO_4^{2-}$) were collected from littoral wetland and midlake sites in L. Enemy Swim on May 19, 1992, and in L. Cochrane on May 20, 1992.

Samples for total P were frozen in polycarbonate bottles, and samples for TKN, $NO_2^-$ + $NO_3^-$-N, and chlorophyll *a* were refrigerated before return to the laboratory. Nitrogen samples were processed the day after collection. The following methods of the U. S. Environmental Protection Agency (25) were used for laboratory analysis: Total Kjeldahl N, 351.3 (colorimetric); $NO_3^-$ -N, 300A (ion chromatography); $NO_2^-$ -N, 354.1 (colorimetric); total P, 365.1 (persulfate digestion, colorimetric); and cations by atomic absorbtion, direct aspiration ($Ca^{2+}$, 215.1; $Mg^{2+}$, 242.1; $Na^+$, 273.1; and $K^+$, 258.1). Chloride and $SO_4^{2-}$ were measured by U.S. E.P.A. method 300.6–1 using ion chromatography (unpublished). Bicarbonate and $CO_3^{2-}$ were calculated from alkalinity (2320 B [28]). Total N was determined by summing TKN, $NO_3^-$ -N, and $NO_2^-$ -N. Nitrate- and $NO_2^-$ -N were summed and statistically analyzed as $NO_3^-$-N + $NO_2^-$-N. Chlorophyll samples were filtered and frozen the same day as collected. Chlorophyll *a* was measured by a modification of the Strickland–Parsons technique (acetone-extraction, colorimetric).

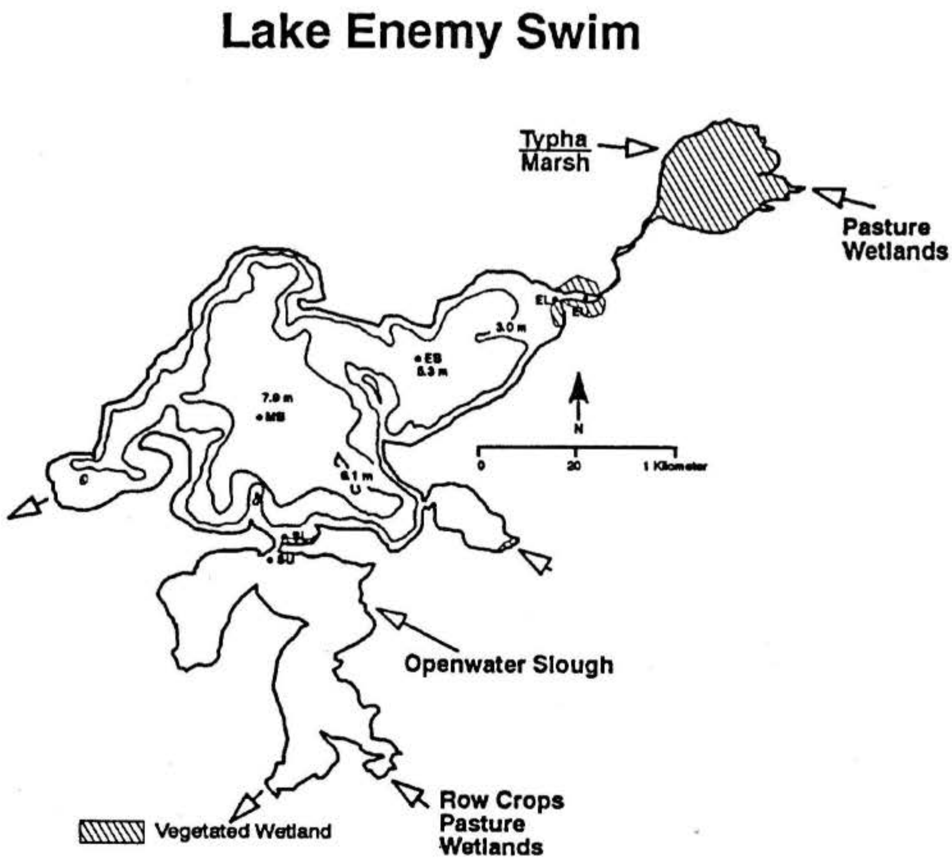


**Fig. 1. Location of sampling stations in Lake Enemy Swim, South Dakota. EU - main inflow upstream, EL - east littoral wetland, EB - center of east basin, MB - center of mid–lake basin, SL - south littoral wetland, and SU - south slough.**

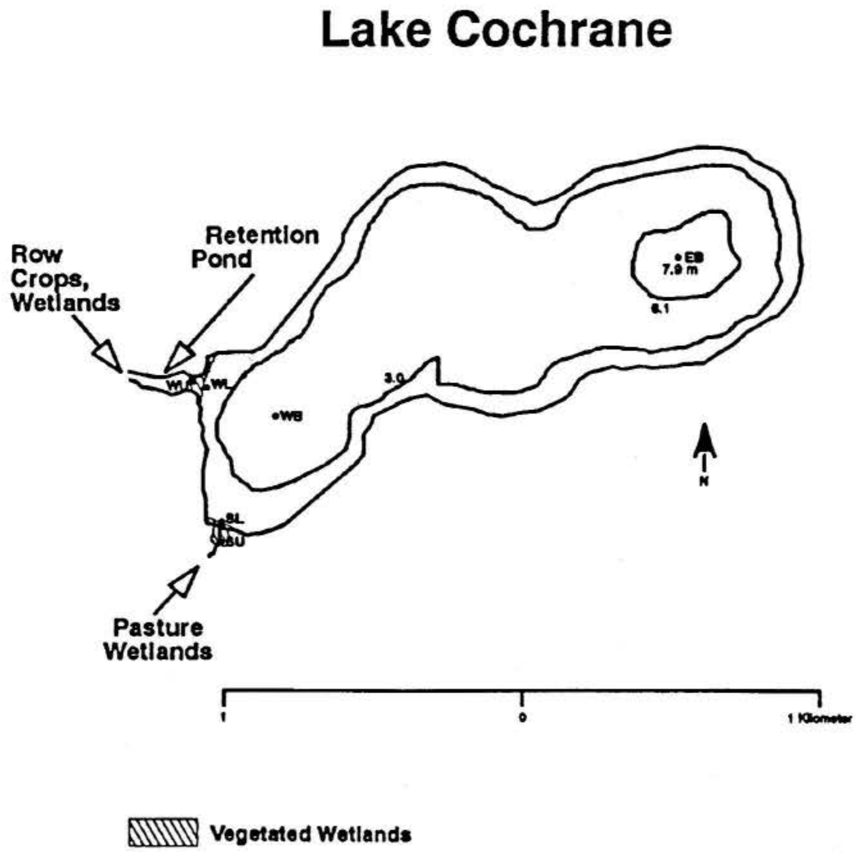


**Fig. 2. Location of sampling stations in Lake Cochrane, South Dakota. SU - south inflow, SL - south littoral wetland, WU - west inflow below sediment retention pond, WL - west littoral wetland, WB - southwest lake basin, and EB - east lake basin.**

Field measurements of temperature, electrical conductivity, and pH were made with a Scout Model probe (Hydrolab Corporation, Austin, TX). On two dates the equipment malfunctioned and temperature was measured with bucket thermometer, pH was determined colorimetrically (Hach Chemical Corp., Loveland, CO, method 17–N) and conductivity was measured with a LaMotte DA DS conductivity meter. Turbidity was measured with a Portable Helege or a Hach 2100 P turbidometer. Water transparency was determined with the use of a 20 cm white and black secchi disk. Field chemical measurements were used for Fe (Hach IR–21) and Si (Hach SI–7 or SI–5, depending on concentration) to minimize loss by phytoplankton uptake before return to the laboratory. Wind velocity was measured with a hand–held wind meter and wind stress was calculated according to Small (29).

Analysis of variance was conducted by using PROC GLM (30). Means of measured concentrations of variables were compared between stations within lakes.

## RESULTS AND DISCUSSION

### Comparison of inflows from vegetated and openwater areas

Inflows to both lakes that drained open water areas (South upstream Table 3 and West upstream Table 4) showed greater concentrations ($P < 0.05$) of total N, TKN and chlorophyll *a* than all other stations in each lake. The inflow to L. Cochrane that drained the sediment retention pond (WU Table 4) also showed higher levels of $NO_3^-$ -N + $NO_2^-$-N, Total P and Si than midlake or littoral zone stations. Nitrate- + $NO_2^-$-N and total P concentrations entering L. Enemy Swim from the slough (SU Table 3) were also elevated. Silica concentrations entering L. Enemy Swim from the slough were lower than from the vegetated inflow (EU Table 3).

Inflows to both lakes that drained vegetated wetlands or grasslands (East upstream Table 3 and South upstream Table 4) had the greatest concentrations of Fe, the least alkaline pH, the least TKN, and the least chlorophyll *a* concentrations. The inflow to L. Enemy Swim that drained the large *Typha* wetland (East upstream Table 3) also had the greatest

**Table 3. Average concentrations of variables measured at six stations in Lake Enemy Swim†.**

| Variable | Station | | | | | |
|---|---|---|---|---|---|---|
| | South | | Mid | East | | |
| | Upstream | Littoral | Basin | Basin | Littoral | Upstream |
| Total-N (mg $L^{-1}$) | 1.24 a (6) | 0.87 b (12) | 0.81 bc (12) | 0.78 bc (12) | 0.83 bc (12) | 0.67 c (6) |
| TKN(mg$L^{-1}$) | 1.21 a (6) | 0.87 b (12) | 0.81 bc (12) | 0.78 bc (12) | 0.81 bc (12) | 0.66 c (6) |
| $NO_2^-$ + $NO_3^-$-N (mg $L^{-1}$) | 0.023 a (6) | 0.002 a (12) | 0.001 a (12) | 0.004 a (12) | 0.020 a (12) | 0.004 a (6) |
| Total-P (mg $L^{-1}$) | 0.055 a (6) | 0.035 bc (12) | 0.030 c (12) | 0.026 c (12) | 0.044 ab (12) | 0.038 abc (6) |
| Silica (mg$L^{-1}$) | 7.8 c (10) | 12.1 b (12) | 12.7 ab (12) | 12.9 ab (12) | 14.6 ab (12) | 15.5 a (10) |
| Iron (mg $L^{-1}$) | 0.033 b (10) | 0.032 b (10) | 0.038 b (10) | 0.038 b (10) | 0.186 a (10) | 0.246 a (10) |
| pH | 8.61 a (4) | 8.50 a (10) | 8.55 a (12) | 8.48 a (12) | 7.89 b (12) | 7.88 b (4) |
| Turbidity (NTU) | 8.30 a (7) | 4.69 bc (11) | 4.61 bc (12) | 5.07 b (12) | 3.28 bc (12) | 1.22 c (6) |
| Chlorophyll *a* (µg$L^{-1}$) | 42.7 a (12) | 11.4 bc (12) | 16.3 bc (12) | 15.1 bc (10) | 20.8 b (10) | 3.5 c (10) |

† Means followed by the same letter are not different (P > 0.05). Number of observations per station given in parenthesis.

**Table 4. Average concentrations of variables measured at six stations in Lake Cochran†.**

| Variable | Station | | | | | |
|---|---|---|---|---|---|---|
| | West | | East | South | | |
| | Inflow | Littoral | Basin | Basin | Littoral | Upstream |
| Total-N (mg $L^{-1}$) | 5.25 a (6) | 1.55 b (12) | 1.41 b (12) | 1.45 b (12) | 1.67 b (12) | 1.55 b (6) |
| TKN (mg $L^{-1}$) | 2.33 a (6) | 1.27 b (12) | 1.37 b (12) | 1.42 b (12) | 1.33 b (12) | 0.73 c (6) |
| $NO_2^-$ + $NO_3^-$-N (mg $L^{-1}$) | 2.92 a (6) | 0.284 bc (12) | 0.037 c (12) | 0.033 c (12) | 0.346 bc (12) | 0.821 b (6) |
| Total-P (mg $L^{-1}$) | 0.161 a (6) | 0.047 bc (12) | 0.038 bc (12) | 0.036 c (12) | 0.057 bc (12) | 0.070 b (6) |
| Silica (mg $L^{-1}$) | 12.9 a (10) | 7.7 bc (12) | 6.8 bc (10) | 5.9 c (12) | 6.7 bc (12) | 10.8 ab (10) |
| Iron (mg $L^{-1}$) | 0.046 b (10) | 0.041 b (10) | 0.023 b (8) | 0.024 b (10) | 0.104 ab (10) | 0.270 a (10) |
| pH | 8.27 a (6) | 8.50 a (10) | 8.33 a (10) | 8.39 a (12) | 8.47 a (12) | 7.88 b (6) |
| Turbidity (NTU) | 5.46 ab (10) | 4.80 ab (12) | 4.06 b (12) | 4.67 ab (12) | 7.60 ab (12) | 9.38 a (10) |
| Chlorophyll *a* (µg$L^{-1}$) | 65.1 a (5) | 24.7 bc (10) | 20.7 bcd (10) | 28.9 b (9) | 17.4 cd (10) | 9.5 d (5) |

† Means followed by the same letter are not different (P > 0.05). Number of observations per station given in parenthesis.

concentrations of Si and the least turbidity of all L. Enemy Swim stations.

**Changes of concentrations in littoral wetlands**

Many variables decreased ($P < 0.05$) after passing from the slough or sediment retention pond through a narrow littoral zone. In L. Enemy Swim, mean concentration of total N decreased 0.37 mg $L^{-1}$, TKN decreased 0.34 mg $L^{-1}$ and chlorophyll *a* decreased 31.3 µg $L^{-1}$ between the SU and SL station (Table 3). In L. Cochrane, mean concentrations of total N decreased 3.70 mg $L^{-1}$, TKN decreased 1.05 mg $L^{-1}$, $NO_3^-$-N + $NO_2^-$-N decreased 2.64 mg $L^{-1}$, Si decreased 5.2 mg $L^{-1}$ and chlorophyll *a* decreased 40.4 µg $L^{-1}$ between the West upstream and West littoral stations (Table 4). Some of the decrease noted in each lake could have been caused by mixing with the water in the lake, as littoral zone samples were taken near the open water side of the littoral zone. In L. Cochrane, however, the samples were collected at the point where water directly entered the lake (West littoral, Figure 2), and the proportion of midbasin water mixing was probably less than in L. Enemy Swim (South littoral, Figure 1).

Inflows to both lakes that drained vegetated areas showed no decreases in nutrients between the upstream sample and the adjacent littoral wetland sample. In both lakes, chlorophyll *a* and TKN concentrations were greater in littoral zones than in the adjacent upstream sample, a result of mixing of midlake water and/or phytoplankton growth in the littoral zone. Chlorophyll *a* increased 17.3 µg $L^{-1}$ ($P < 0.05$) between the East upstream and East littoral station in L. Enemy Swim (Table 3) and TKN increased 0.60 mg $L^{-1}$ ($P < 0.05$) between the South upstream and South littoral station in L. Cochrane (Table 4).

**Changes in concentrations in midlake areas**

Iron decreased 0.148 mg $L^{-1}$ ($P < 0.05$) between the L. Enemy Swim East littoral and East basin sites, coincident with an increase in pH (Table 3). No other significant changes were noted between littoral zone and midlake areas.

Midlake areas were different ($P < 0.05$) from upstream areas in several variables that did not vary significantly between the upstream area and the littoral zone or between the littoral zone and the midlake basin. Between the East upland and East basin sites in L. Enemy Swim, turbidity increased 3.85 NTU (Table 3). Between the L. Cochrane South upstream and East basin sites, Fe decreased 0.246 mg $L^{-1}$, $NO_3^-$- + $NO_2^-$-N decreased 0.788 mg $L^{-1}$, total phosphate decreased 0.034 mg $L^{-1}$ and chlorophyll *a* increased 19.4 µg $L^{-1}$ (Table 4).

**Comparison of inflows from upstream vegetated wetlands with inflows from upstream open water basins.**

Three of the four upstream basins probably received high nutrient inputs. Many cattle were pastured on hilly terrain with depleted vegetation, immediately upstream from the *Typha* marsh east of L. Enemy Swim. Row crops were cultivated on sloping land adjacent to the open water slough south of L. Enemy Swim, and upstream from the sediment retention basin west of L. Cochrane. Only light grazing was present in the pasture–wet meadow south of L. Cochrane.

Water coming from the *Typha* marsh (L. Enemy Swim East upstream) had the least concentrations of total N, total P, chlorophyll *a*, and turbidity of all upstream stations (Tables 3 and 4). Also, we discontinued our measurements after August, when wetland nutrient export is likely to be greater (3). However, nutrients exported in the fall are more likely to be deposited in lake sediments and not trigger algal blooms (31).

Water coming from the sediment retention basin (L. Cochrane West upstream) had the largest concentrations of total N, total P and chlorophyll *a* of all stations (Tables 3 and 4). Water coming from the open water slough (L. Enemy Swim South Upstream) also had large concentrations of the above variables. Other authors found open water retention basins to more effectively remove nutrients than vegetated natural wetlands (32), particularly if the basins are deep enough (33) and have a surface area greater than 1% of the drainage basin (34). The open water slough south of L. Enemy Swim has a surface area greater than 1% of the drainage basin. However, shallow depth (< 3 m) and lack of emergent vegetation permit sediment and nutrient resuspension by wave action (35). Large chlorophyll *a* concentrations (Table 3) and phytoplankton cell counts (Haertel and Duffy, unpublished) indicate that nutrients are being transported into L. Enemy Swim from the slough by phytoplankton.

The constructed sediment retention basin is too deep to permit sediment resuspension by wave action, and the outflow is from the surface. However, Chlorophyll *a* concentrations (Table 4) and cell counts at L. Cochrane West upstream (Haertel and Duffy, unpublished) indicate that nutrients are also being transported into L. Cochrane from the sediment retention basin, in part, by phytoplankton. Although the sediment retention basin has a surface area of less than 1% of the drainage basin, it is unlikely that increasing the surface area of the basin would prevent phytoplankton blooms. Our results confirm that emergent vegetation is likely to decrease N and P export from wetlands during the growing season by shading out the phytoplankton (12).

The vegetated wetlands additionally contribute large concentrations of Si (Tables 3 and 4). Silica concentrations are small in the open water slough undoubtedly from diatom uptake and slower recycling of Si than P from the sediments (36). The ratio of different nutrients influences plankton composition (37). A high Si:P ratio promotes the growth of diatoms whereas a low Si:P ratio promotes the growth of bluegreen algae (17). Mean dissolved Si to total P ratios, by weight, ranked from greatest to least, were 408:1 downstream from the *Typha* marsh, 154:1 downstream from pasture–wet meadow, 142:1 downstream from the open water slough, and 80:1 downstream from the sediment retention basin.

The vegetated wetlands also deliver high levels of Fe (Figures 3 and 4). Iron precipitates phosphate from lake water (38). Iron also influences the composition of the phytoplankton by limitation of phytoplankton growth (39). Bluegreen algae are better competitors for Fe (18), but N fixation requires larger amounts of Fe (38). The Fe:P ratios downstream from the *Typha* marsh were 6:1, from pasture–wet meadow 4:1, from open water slough 0.6:1, and from sediment retention basin 0.3:1.

**Changes within littoral zone wetlands downstream from open water basins.**

Significant reductions of P, N, Si (L. Cochrane only), and chlorophyll *a* occurred in littoral wetlands downstream from open water basins (Tables 3 and 4). Factors contributing to those reductions may have included sedimentation, denitrification, ammonia volatilization, and formation of Fe–P complexes (40). Oxidation of sediments by vascular plants (41) may have enhanced nitrification and denitrification. Diatom periphyton particularly remove Si from water and insect and vertebrate herbivory removes all nutrients. Rapid exchange between littoral zone and limnetic zone waters also contributes to lowering nutrient concentrations at the littoral zone sites (15).

The Si:P, Si:N, and Fe:P ratios were larger in the L. Enemy Swim south littoral wetland than at the adjacent upstream station (Si:P, 346:1 vs. 142:1; Si:N, 14:1 vs. 6:1; and Fe:P, 0.9:1 vs. 0.6:1). Some change may have been caused by mixing with midlake waters, as L. Enemy Swim midlake ratios were Si:P, 423:1; Si:N, 16:1; and Fe:P, 1.3:1. The L. Cochrane west littoral wetland also had larger Si:P ratios than the adjacent upstream station (164:1 vs. 80:1) and lesser than the adjacent midlake station (179:1). The Si:N was greater in the L. Cochrane west littoral zone (5.0:1) than the adjacent upstream station (2.5:1) but similar to the adjacent midlake basin (4.8:1). The Fe:P was greater in the west littoral zone station (0.9:1) than either the upstream station (0.3:1) or the midlake station (0.6:1 Fe:P), suggesting that littoral zone processes were responsible for the increase.

Large densities of phytoplankton species of composition similar to that of the upstream slough were sometimes present in the L. Enemy Swim south littoral wetland (Haertel and Duffy, unpublished). This resulted in increased turbidity and may have contributed to the decreased macrophyte diversity observed at this station (Table 2) through light limitation (42) and possible bluegreen algal toxins (43).

**Changes within littoral zone wetlands downstream from vegetated basins.**

Both littoral zone wetlands located downstream from vegetated basins received water that was already low in total N, total P and chlorophyll *a* concentrations and already high in Fe and Si concentrations (East upstream Table 3, South upstream Table 4). Thus, it is not surprising that these littoral wetlands did not further reduce total N, total P and chlorophyll *a* concentrations, and did not increase Si:P, Si:N and Fe:P ratios.

Mean concentrations of total N, total P, and chlorophyll *a* actually were greater in the L. Enemy Swim east littoral wetland than both adjacent upstream and open water stations (Table 3). Lakeside cottages, free–ranging cattle, and water birds were all present, and may have contributed to increased nutrient loading. In the L. Cochrane south littoral wetland, total N and chlorophyll *a* concentrations, increased, but total P concentrations decreased (Table 4). Cattle did not have access to L. Cochrane, but nearby cottages may have contributed nutrients from human activities.

## CONCLUSIONS

Greatest concentrations of N and P were consistently found in water entering both lakes from open water wetlands. In contrast, water entering both lakes through vegetetated wetlands had lesser concentrations of N and P. Water entering from vegetated wetlands also had high concentrations of dissolved Si and Fe, leading to high ratios of Si and Fe relative to N and P. Least chlorophyll *a* concentrations were also recorded in water originating in vegetated wetlands. In L. Enemy Swim., the overall better quality of water originating from a vegetated upstream wetland was associated with richness in macrophyte species in the downstream littoral zone. Poorer quality water entering the lake from an open water wetland was associated with fewer macrophyte species in the downstream littoral zone.

Lesser concentrations of total N and total P, and the greater Si concentrations found downstream from vegetated wetlands are likely to improve lake water quality. These changes increase the competetive abilities of diatom phytoplankton, which is more easily incorporated into lacustrine food chains than bluegreen phytoplankton (44) and translated into increased fish production (31). The open water slough and settling pond did not provide the same beneficial effect, but instead, discharged water with high levels of N and P in the form of phytoplankton.

Lake water quality will be enhanced by the protection of both littoral zone and upstream vegetated wetlands. Where such wetlands do not exist, it may be beneficial to create them, particularly downstream from open water sloughs and sediment retention basins.

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