Direct and Indirect Impacts of Submersed Aquatic Vegetation on the Nutrient Budget of an Urban Oxbow Lake

by William F. James, John W. Barko, and Harry L. Eakin

PURPOSE: The purpose of this research was to quantify direct and indirect contributions to the phosphorus budget of Half Moon Lake, Wisconsin, by submersed aquatic macrophytes.

Background: Submersed aquatic macrophytes can play an important role in the phosphorus budget of aquatic systems; thus, their impacts need to be considered in lake management and rehabilitation plans. In particular, macrophytes can directly recycle phosphorus from the sediment via root uptake, incorporation into tissue, and subsequent senescence (Barko and Smart 1980; Carpenter 1980; Landers 1982; Smith and Adams 1986; Barko and James 1998). They can also indirectly recycle phosphorus from the sediment via increasing pH in the water column through photosynthetic activities. Phosphorus release from sediments can be enhanced at high pH as a result of ligand exchange on iron oxides contained in the sediment (Drake and Heaney 1987). These processes can lead to phosphorus enrichment of aquatic systems and eutrophication. The objectives of this study were to evaluate direct and indirect impacts of a near monotypic stand of *Potamogeton crispus* L. on the phosphorus economy of Half Moon Lake.

STUDY SITE: Half Moon Lake is a small oxbow of the Chippewa River located in Eau Claire, WI (population of 55,000). Morphological and watershed characteristics are reported in Barr Engineering (1992). Table 1 summarizes information from that report pertinent to the present study.

Table 1
Morphological Characteristics of Half Moon Lake (Barr Engineering 1992)

Morphological Characteristics	
Surface Area, m^2	534,590
Volume, m^3	890,596
Maximum Depth, m	4.3
Mean Depth, m	1.7

Inflows to Half Moon Lake include eight storm sewers that discharge into the lake. Other water sources to the lake include groundwater that is pumped from wells located at a pumping facility situated southeast of the lake on the Chippewa River. The outlet structure is located in the southwest portion of the lake. It consists of an uncontrolled surface structure that drains water from the lake when pool elevation exceeds 234.5 m National Vertical Geodetic Datum (NVGD). The lake is currently eutrophic and exhibits high algal and aquatic macrophyte growth (Borman 1990; Brakke 1995; Konkel and Borman 1996). Dense, near-monotypic stands of *Potamogeton crispus* in early summer have led to mechanical harvesting since 1982 to provide boating lanes for recreational use (Konkel and Borman 1996).

METHODS

***Potamogeton crispus* Decay.** In early June (1-5 June), biomass sampling was conducted in Half Moon Lake to quantify biomass (dry mass) and macrophyte phosphorus near the time of *P. crispus* senescence (mid- to late June). The lake was divided into six approximately equal regions for macrophyte sampling purposes. In each region, one transect with three sampling stations was established perpendicular to the shoreline on each side of the lake (Figure 1). The locations of transects and stations in each region were determined randomly.

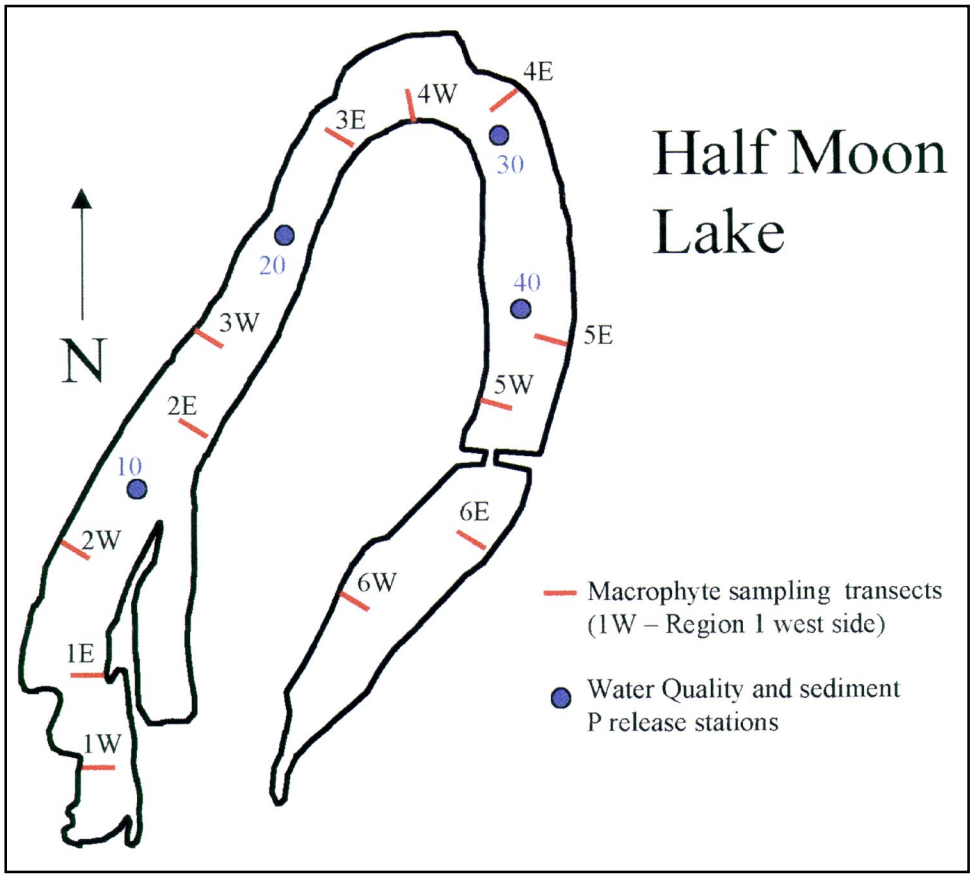

Figure 1. Sediment sampling stations and macrophyte transect locations in Half Moon Lake

Three replicate samples were collected at each station using a quadrat sampler. A total of nine samples were collected along each transect. Overall, a total of 108 samples were collected throughout the lake. The quadrat sampler consisted of a sheet metal enclosure measuring 0.75 m by 0.75 m. The length of the sampler was 1.5 m. The sampler was lowered using a winch to enclose a sediment area. A rake was used to carefully pull macrophytes from the area enclosed by the sampler. Several rake passes were conducted to ensure that all the macrophytes were removed from within the quadrat sampler. The macrophyte samples were thoroughly rinsed to remove sediment and placed in a mesh bag for fresh weight analysis.

On the shore, macrophyte samples were spun down using a washing machine to remove excess water and weighed to the nearest 1 mg for fresh weight determination. Randomly chosen samples (about 15 percent of the samples) were also dried at 70 ºC to determine a fresh weight:dry weight

conversion factor. Fifteen randomly chosen macrophyte samples were analyzed for tissue phosphorus content according to Allen et al. (1974).

Lakewide macrophyte biomass and phosphorus content in the lake near the time of *P. crispus* senescence in June were estimated by weighting estimates with respect to sediment area represented by each transect and region. Since macrophytes were harvested by the City of Eau Claire between May and mid-June, the amounts of macrophyte biomass and tissue phosphorus removed from the lake via this mechanism were estimated by obtaining truck weights before and after filling the hopper with harvested macrophytes.

To determine *P. crispus* breakdown, plants were removed from different regions of the lake and spun down in a washing machine to remove excess moisture. A known mass (100 g fresh weight) of macrophyte tissue was placed in replicate mesh bags (2-mm mesh size). The mesh bags containing plant material were air-dried for approximately 3 days to initiate plant death before deployment in the lake. On 14 June, replicate mesh bags were deployed in the lake at mid-water column depth (~1.2 m) at station 10 (Figure 1). On days 2, 5, 7, 14, 30, 58, and 90, five replicate bags were removed from the lake for analysis of loss of mass and changes in phosphorus content. In the laboratory, macrophyte material was carefully washed to remove sediments and other debris, then dried at 70 ºC to a constant weight. Subsamples of tissue were analyzed for phosphorus (see above methods).

On days 0, 14, and 30 of *P. crispus* breakdown, studies were conducted to determine the rate of phosphorus leaching from macrophyte tissue. Subsamples of macrophyte tissue contained in the mesh bags were placed in 1-L beakers containing filtered lake water and incubated in an environmental chamber at 20 ºC. At time intervals ranging from several minutes to days, water samples were collected for the determination of soluble reactive phosphorus (SRP) concentration using the ascorbic acid method (American Public Health association (APHA) 1992). Rates of phosphorus leaching were calculated as the change in milligrams SRP per gram dry mass of plant material per day.

Sediment. In August of 1999, nine replicate intact sediment cores were collected from the profundal sediments of stations 10, 20, 30, and 40 (Figure 1), for determination of rates of SRP release from the sediment. Sediment cores were collected using a Wildco KB sediment core sampler (Wildco Wildlife Supply Co.) equipped with an acrylic core liner (6.5-cm ID and 50-cm length). Additional lake water was collected from the epilimnion for incubation with the collected sediment. Overall, a total of 36 sediment cores were collected for examination of phosphorus release from sediments in Half Moon Lake.

Sediment systems, constructed according to the methods of James et al. (1995), were incubated in an environmental chamber at 20 ºC for 1-2 weeks. One set of three replicate sediment incubation systems was subjected to an oxic environment while the other set (three replicates) was subjected to an anoxic environment for each station. The oxidation-reduction environment in each system was controlled by gently bubbling either air (oxic) or nitrogen (anoxic) through an air stone placed just above the sediment surface. Bubbling action ensured complete mixing of the water column but did not disrupt or resuspend the sediment. A third set of replicate sediment incubation systems was subjected to an oxic environment and high pH (~9.0) by bubbling with CO_2-free air. Water samples were collected daily from the overlying water of each sediment system, filtered through a 0.45-µm

membrane filter, and analyzed for SRP. Rates of phosphorus release from the sediment ($mg/m^{-2}/d^{-1}$) were calculated as linear changes in phosphorus mass in the overlying water (corrected for dilution effects due to daily replacement of lake water) divided by time and the area of the incubation system.

Dissolved oxygen concentrations and pH were monitored biweekly at 1-m depth intervals in the summer at the sediment sampling stations using a Hydrolab Data Sonde 4 (Hydrolab, Inc.). The probes were calibrated with independently derived measurements of dissolved oxygen using the Winkler technique (APHA 1992) and known pH buffer solutions.

RESULTS

***Potamogeton crispus* Biomass and Decomposition.** During the period May through mid-June, approximately 9,000 kg biomass (dry mass) and 30 kg macrophyte phosphorus were harvested from Half Moon Lake (Figure 2). The estimated whole-lake macrophyte biomass and phosphorus mass remaining in Half Moon Lake after final harvesting on 13 June was 25.4 g/m^2 (± 2.3 standard error (S.E.), n=108) and 111.6 mg/m^2 (± 9.9 S.E.), respectively (Table 2). Lakewide biomass and macrophyte phosphorus available for flux to the water column (assuming complete decomposition) at that time was 13,600 kg and 60 kg, respectively. The phosphorus content of *P. crispus* in June was 0.42 percent (±0.012 S.E.).

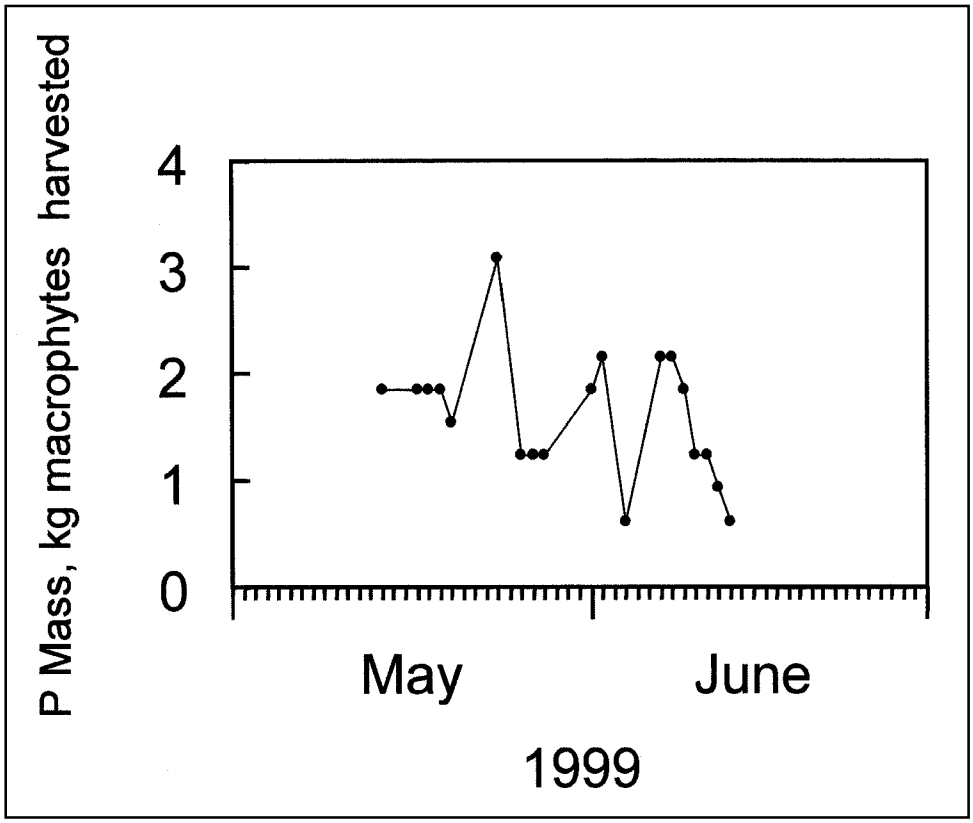

Figure 2. Time series of the mass of macrophyte phosphorus harvested from Half Moon Lake for various days in May and June

Table 2
Mean (1 standard error in parentheses; n=18 for each region) Estimates of *P. crispus* Biomass and Phosphorus Concentration in Various Regions (see Figure 1) of Half Moon Lake in Early June 1999[1]

Region	Biomass, g/m^{-2}	P, mg/m^{-2}
1	51.2 (4.3)	216.3 (18.1)
2	30.1 (4.4)	127.0 (18.4)
3	24.4 (4.5)	102.9 (18.9)
4	31.0 (5.5)	130.9 (23.1)
5	25.4 (5.9)	107.1 (24.8)
6	28.6 (6.9)	120.6 (29.3)
Lakewide biomass (uncorrected for harvesting)	31.1 (2.3)	131.1 (9.9)
Lakewide biomass (corrected for harvesting)	25.4	111.6

[1] The lakewide biomass and phosphorus concentration uncorrected for harvesting represents the overall mean (1 standard error in parentheses) in early June. The lakewide biomass and phosphorus concentration corrected for harvesting represents the overall mean corrected for macrophyte biomass that was harvested from the lake after the biomass sampling.

Mesh bag decomposition experiments in Half Moon Lake found that the loss of phosphorus from *P. crispus* was greatest during the first week of decomposition, with 40 percent of the phosphorus loss occurring during the first 2 days (Figure 3). Leaching of soluble phosphorus from plant tissue (i.e., autolysis) into the water, measured using laboratory incubation systems, was greatest during the first 24 hr of decomposition (Figure 4). On days 14 and 30 of decomposition, leaching of phosphorus from plant tissue was minor (Figure 4), but fragmentation, breakdown, and loss of plant tissue phosphorus, which most likely occurred via bacterial degradation, continued between day 14 and day 30 of decomposition (Figure 3). Within 30 days, nearly all of the phosphorus mass was lost from the mesh bags (Figure 3).

Estimates of *P. crispus* biomass in June were combined, corrected for material removed by harvesting, with rates of leaching and breakdown normalized with respect to the lake surface area to estimate lakewide rates of *P. crispus* decomposition. In general, leaching of phosphorus directly into the water column dominated the decomposition process during the early stages, while breakdown of phosphorus via microbial degradation and fragmentation dominated the later stages of decomposition (Figure 5). The integrated, lakewide decomposition rate over the 30-day period (Figure 5) was normalized over a 3-month period (June-August; the period of high algal biomass in the lake) for comparison with rates of phosphorus release from sediments and other internal and external sources. This summer *P. crispus* decomposition rate was1.2 $mg/m^{-2}/d^{-1}$ (Table 3).

Sediment Phosphorus Sources. Rates of phosphorus release from sediments, measured in the laboratory, were substantial under anoxic conditions, ranging between a mean of 2.3 and 11.7 $mg/m^{-2}/d^{-1}$ for the four in-lake stations (Figure 6). Rates of phosphorus release under oxic conditions were also high and varied linearly as a function of pH (Figure 7). At pH values near 7.0,

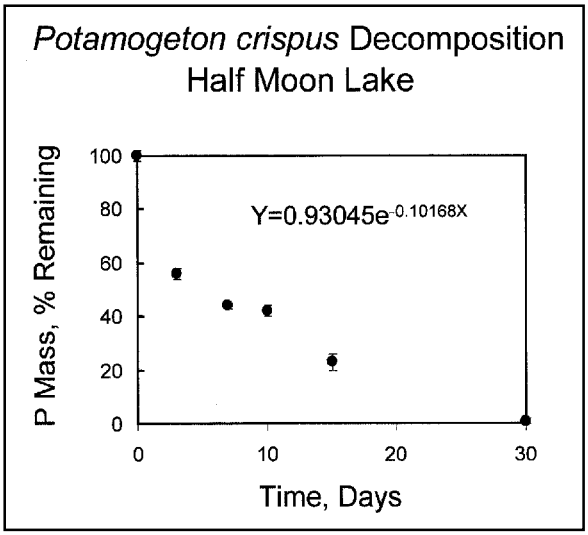

Figure 3. Percent phosphorus mass remaining in decomposing *Potamogeton crispus* contained in mesh bags at station 10 in Half Moon Lake as a function of time

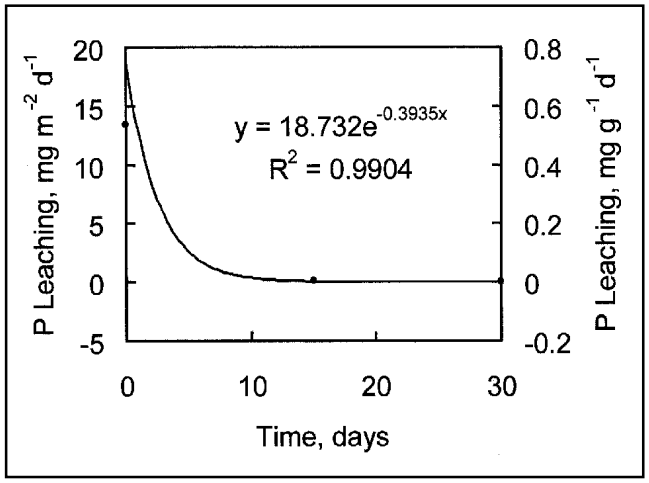

Figure 4. Rates of phosphorus leaching from *Potamogeton crispus*, measured in laboratory systems, as a function of time. Macrophyte tissue contained in mesh bags was removed from the lake at days 0, 15, and 30. Samples were incubated in laboratory systems containing filtered lake water at 20 ºC. Changes in soluble reactive phosphorus through time in the systems were used to determine rates of phosphorus leaching

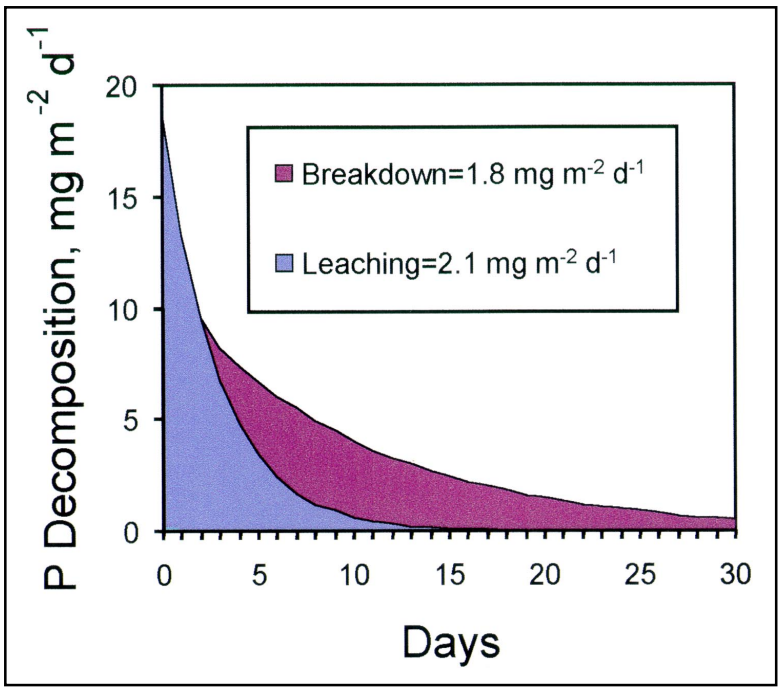

Figure 5. Variations in *Potamogeton crispus* decomposition via leaching and breakdown. Leaching is defined as autolysis of cellular contents into the water column while breakdown refers to microbial decomposition and fragmentation

Table 3
Lakewide Summer (June-August) Phosphorus Loading Rates from Various Sources to Half Moon Lake. All Rates were Adjusted with Respect to Lake Surface Area and the 3-Month Summer Period

Loading Variable	Source	$Mg/m^{-2}/d^{-1}$	Percent
External P load, $mg/m^{-2}/d^{-1}$	Storm sewers[1]	0.3	5
	Pumps[1]	0.4	7
	Precipitation[2]	0.5	9
Internal P load, $mg/m^{-2}/d^{-1}$	Sediment[3]	2.5	42
	P. crispus decomposition[3]	1.2	20
	Motor boat activity[1]	1.0	17
Total		5.9	100

[1] James et al. (2000).
[2] P concentrations were not directly measured in rainwater. Literature values were used to estimate loading from this source (Wetzel 1975).
[3] This study.

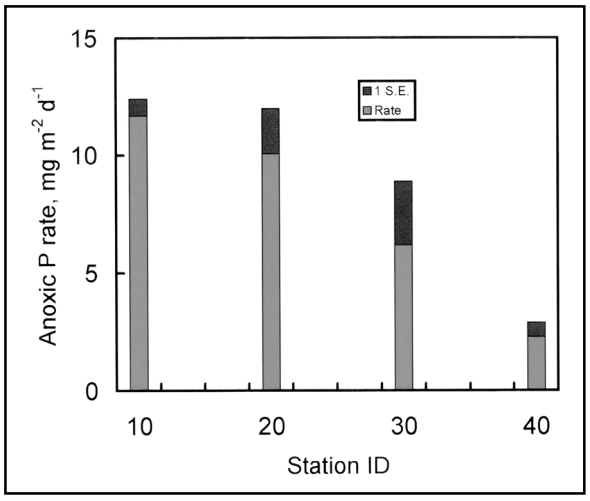

Figure 6. Mean (± 1 S.E.) rates of phosphorus release from sediments under anoxic conditions. Rates were determined in laboratory incubation systems at 20 ºC

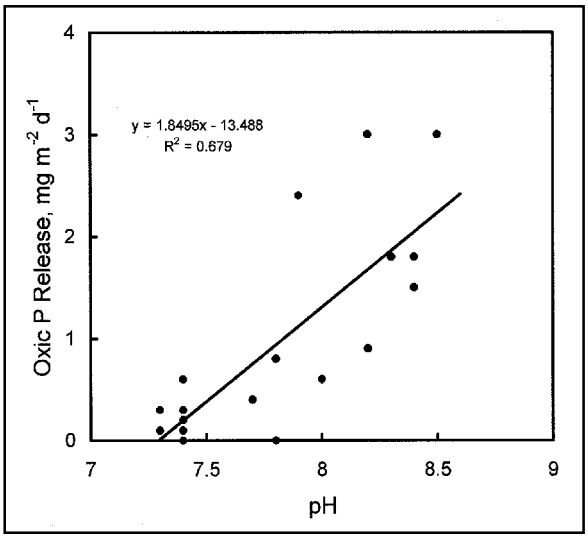

Figure 7. Variations in rates of phosphorus release from sediments under oxic conditions as a function of pH. Rates were determined in laboratory incubation systems at 20 ºC

rates of phosphorus release under oxic conditions were < 0.5 $mg/m^{-2}/d^{-1}$. At pH values near 8.5, rates of phosphorus release under oxic conditions were substantially greater at approximately 2 to 3 $mg/m^{-2}/d^{-1}$.

In Half Moon Lake, the bottom waters at several stations exhibited anoxic conditions during June through September (Figure 8). During periods of anoxia, the pH of the bottom waters declined below 7.5 (Figure 8). In contrast, pH approached 10.0 in late April and was greater than 8.0 in May through June and mid-August through September. Fluctuations in pH and the occurrence of anoxia

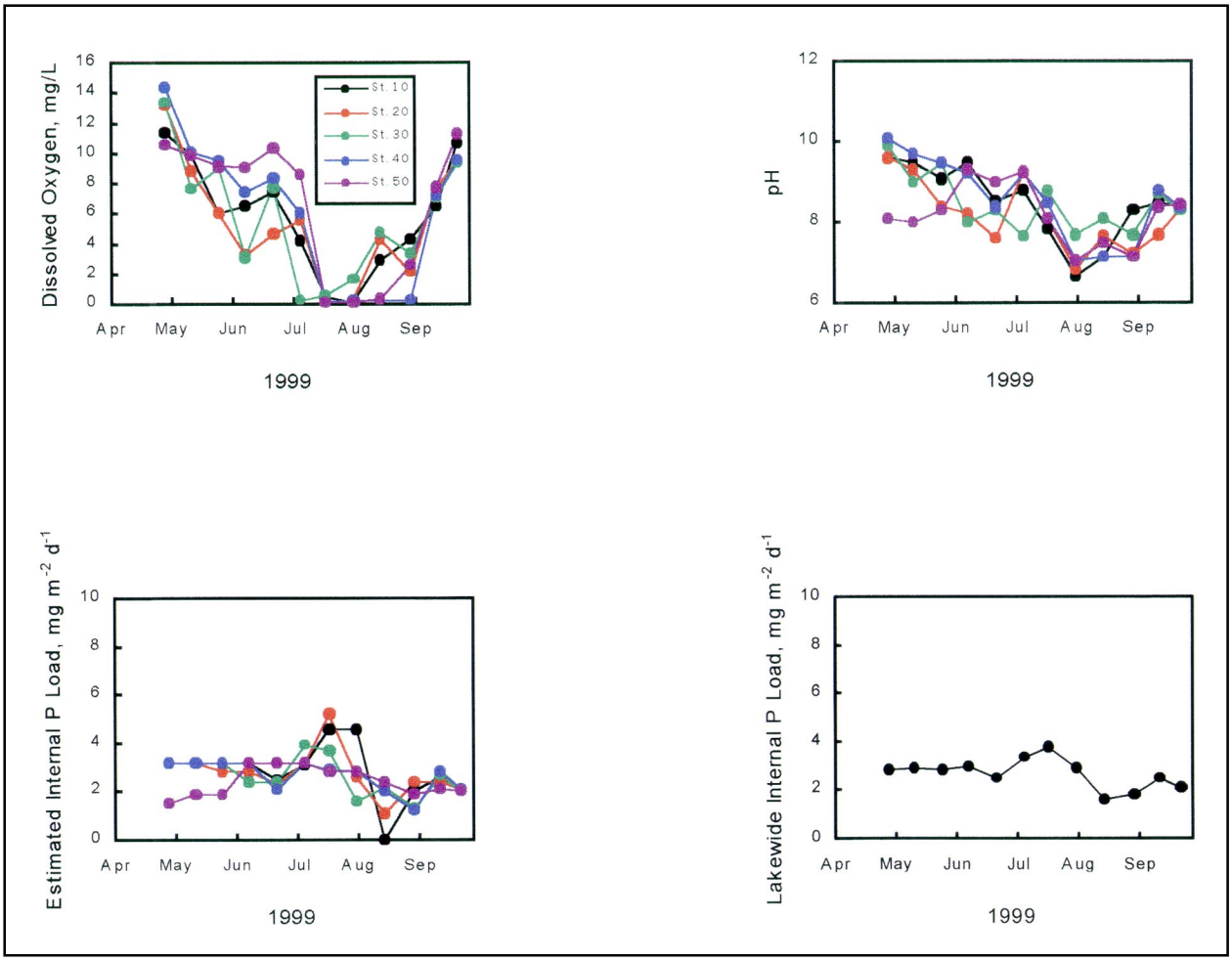

Figure 8. Seasonal variations in near-bottom dissolved oxygen concentration, near-bottom pH, the estimated internal phosphorus load from sediments, and the lakewide internal phosphorus load from sediments. The internal phosphorus load from sediments was estimated using rates of phosphorus release as a function of redox and pH and measured oxygen and pH conditions in the lake. The lakewide rate of internal phosphorus loading from the sediment was estimated by weighting rates with respect to area from each station

throughout the entire water column were used to estimate a lakewide rate of phosphorus release from sediment during the summer period (Figure 8). In general, the estimated lakewide rate was greatest in July, coincident with the occurrence of bottom water anoxia (Figure 8). The estimated lakewide rate of phosphorus release from sediment for the summer period (June through August) was 2.5 $mg/m^{-2}/d^{-1}$ (Table 3).

DISCUSSION: *P. crispus* decomposition provided an important internal source of phosphorus to the lake water column, accounting for approximately 26 percent of the measured internal phosphorus load during the summer (Table 3). Even at a relatively low biomass level of 25 g/m^{-2} near the time of plant decomposition, the internal phosphorus loading rate via decomposition was high at 1.2 $mg/m^{-2}/d^{-1}$. Since it appeared that most of the phosphorus flux occurred within 2 weeks of plant senescence, based on loss of tissue phosphorus in mesh bags and leaching studies, the authors believe that impacts on the phosphorus budget via this mechanism were confined primarily to the month of June, when plant senescence occurred. Harvesting was important in reducing the biomass and phosphorus content level near the time of plant senescence, as it removed an estimated 16 g/m^{-2}

biomass and 56 mg/m^{-2} tissue phosphorus. This removal of biomass represented approximately 30 percent of the overall biomass and plant phosphorus in the lake available for decomposition in early June. Had harvesting and removal of plant tissue phosphorus from the system not occurred prior to plant senescence, the predicted rate of internal phosphorus loading via plant decomposition would have been nearly two times greater at 2.2 mg/m^{-2}/d^{-1}.

Sediment represented the greatest internal phosphorus load to the lake, accounting for 53 percent of the total internal phosphorus load (Table 3). Rates of phosphorus release from sediments were high under anoxic conditions and comparable to those rates measured for other eutrophic systems (Nürnberg et al. 1986). One mechanism of phosphorus release under reducing conditions is iron-phosphorus disassociation (Mortimer 1971). Under oxidized conditions, iron has a high binding affinity for phosphorus (Lijklema 1977). However, phosphorus bound to iron hydroxides can desorb and diffuse into the sediment porewater and the water column as iron compounds are reduced from Fe^{+3} to Fe^{+2} under conditions of hypolimnetic anoxia. Asplund (1996) measured high concentrations of sediment iron and iron-aluminum bound sediment phosphorus for sediments collected in Half Moon Lake, suggesting that iron-phosphorus interactions are important and likely contribute to sediment phosphorus release in this lake.

The pH also appeared to play an important role in affecting the rate of phosphorus release from sediments under oxic conditions, as there was a strong positive and linear relationship between pH and the rate of phosphorus release under oxic conditions. We could not, however, reliably determine rates of phosphorus release from sediments at pH values exceeding approximately 8.6 units in our laboratory systems using, for instance, NaOH additions to increase pH. Boers (1991) demonstrated that NaOH additions to sediment-water incubation systems for purposes of elevating pH (versus stripping CO_2 from the water column) resulted in artificially enhanced rates of phosphorus release from systems due to increases in alkalinity of the sediment porewater. Nevertheless, others have demonstrated linear relationships between phosphorus release from sediments and pH (Boers 1991; James et al. 1996). Enhanced phosphorus release at high pH (and high hydroxyl ion (OH^-) concentration) is thought to occur via ligand exchange and replacement of PO_4^- with an OH^- ion on oxidized iron compounds (Drake and Heaney 1987). Photosynthesis by aquatic plants and algae in Half Moon Lake, which is primarily responsible for elevating pH in aquatic systems, appeared to provide a mechanism of enhancing phosphorus release from sediments under oxic conditions. Thus, in addition to direct impacts on the phosphorus budget via decomposition, submersed macrophytes also played an indirect role in recycling phosphorus by elevating pH and stimulating phosphorus release from sediments via ligand exchange.

RECOMMENDATIONS: Results suggest that submersed macrophytes can play an important role in recycling phosphorus directly via decomposition and leaching and indirectly via increasing ligand exchange on phosphorus-rich sediments through photosynthetic activities and elevated pH. Mechanical harvesting appears to be a viable management option not only for temporarily reducing nuisance plant biomass, but also for reducing phosphorus recycling in aquatic systems via these recycling pathways. Phosphorus sources to the lake from decomposing *P. crispus* could be reduced by greater harvesting and removal of plant phosphorus from the lake prior to *P. crispus* senescence, which typically occurs in mid- to late June. For instance, a target of 50 percent removal of typical biomass (i.e., approximately 40 g/m^{-2}) by mid-June could decrease phosphorus flux from decomposing plants by approximately 50 percent, because more plant phosphorus is removed from the system prior to *P. crispus* senescence.

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POINTS OF CONTACT: This technical note was written by Messrs. William F. James and Harry L. Eakin of the Eau Galle Aquatic Ecosystem Research Facility, Environmental Laboratory (EL), Engineer Research and Development Center (ERDC), and Dr. John W. Barko, EL, ERDC. For additional information, contact the managers of the Aquatic Plant Control Research Program, Dr. Barko (601-634-3654, *John.W.Barko@erdc.usace.army.mil*) or Mr. Robert C. Gunkel (601-634-3722, *Robert.C.Gunkel@erdc.usace.army.mil*). This technical note should be cited as follows:

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