



Macrophyte Management via Mechanical Shredding: Effects on Water Quality in Lake Champlain (Vermont-New York)

INTRODUCTION: Control of large expanses of aquatic macrophytes with conventional harvesting or herbicide application techniques is often impractical and/or cost-prohibitive. One alternative control measure for these cases is mechanical shredding of macrophytes without harvesting (i.e., clipping or shredding plants and leaving biomass in the system). In particular, mechanical shredding may be very promising for control of monospecific stands of nonnative macrophytes like the water chestnut (*Trapa natans*), which has invaded large regions of Lake Champlain (Vermont-New York).

Dense macrophyte stands can mobilize nutrients such as phosphorus and nitrogen directly by root uptake and senescence (Barko and Smart 1980, Carpenter 1980, Smith and Adams 1986). Mechanical shredding of macrophytes without harvesting from the system may enhance nutrient recycling directly via leaching from tissues during autolysis and decomposition (Jewell 1971, Nichols and Keeney 1973) and indirectly via enhancing dissolved oxygen depletion and shifts in redox, which favors nutrient release from sediments (Nürnberg 1987). These processes can potentially impact the nutrient economy and productivity of aquatic systems and, thus, need to be examined with respect to macrophyte management.

The objectives of this study were to examine changes in various in situ (i.e., dissolved oxygen, turbidity) and chemical constituents (i.e., nitrogen and phosphorus) in the water column, contributions of nutrients from decomposing macrophytes, and rates of nitrogen and phosphorus exchange at the sediment-water interface in mechanically controlled versus untreated stands of *T. natans* in Lake Champlain (Vermont-New York).

MATERIALS AND METHODS

Study Site. *Trapa natans* is an exotic annual aquatic macrophyte that has been a management problem in Lake Champlain for decades. It currently occupies approximately 300 acres of the southern portion of the lake. Control and experimental stations were established within 10,000-m² plots (200 m by 50 m) established in Pickerel Bay and Peters Bay of Lake Champlain, respectively (Figure 1) for examination of water quality characteristics and changes as a result of mechanical shredding. The water column depth at each station was approximately 0.75 m. Mechanical shredding (Penny System) of the experimental site occurred on 26 July 1999.

Water Column Profiling. Water samples for nutrient analyses were collected at each station 2 days prior to mechanical shredding (i.e., 24 July) and on days 1, 4, 7, and 15 after mechanical shredding. Vertical profiles of total phosphorus, soluble reactive phosphorus (SRP), total nitrogen, and ammonium-N (NH₃-N) were collected on these days at approximately 0.125 m using a pneumatically driven close-interval syringe sampler as described by James and Barko (1991). Water for analysis of soluble constituents was filtered in situ by attaching 0.45- μ m membrane filters to

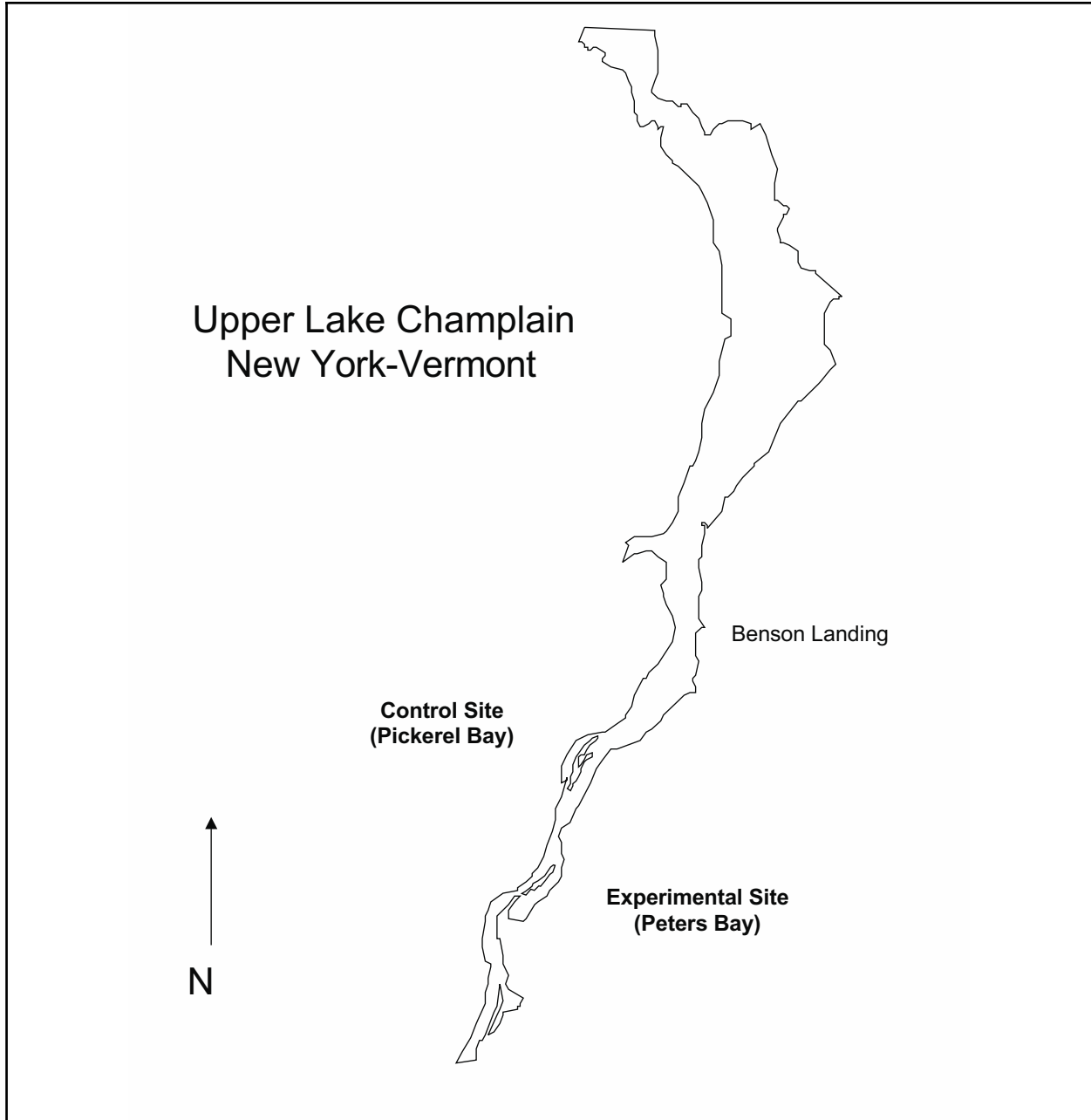


Figure 1. Location of control and experimental stations in Lake Champlain

syringes. Nitrogen and phosphorus were analyzed using automated analytical techniques (Zellweger Analytics, Lachat Division, Milwaukee, WI). Total nitrogen and phosphorus samples were digested using alkaline persulfate (Ameel, Aner, and Owen 1993) prior to analysis.

Water samples for viable chlorophyll analyses were collected at each station 2 days prior to mechanical shredding and on day 7 after mechanical harvesting. Samples integrated over the upper 1-m water column were collected using an integrated sampler (Barko et al. 1984), which consisted of a 1.5-in. PVC pipe with a one-way check valve attached to the base of the pipe. When the pipe was lowered into the water column down to the 1-m depth, the check valve remained open, allowing

water to pass freely through the pipe. When the sampler was raised from the water column, the check valve closed, trapping a water sample integrated over the upper 1-m depth. Samples were poured into an amber bottle and immediately cooled on ice before shipment to the laboratory. They were filtered within 24 hr, extracted in a 50:50 solution of acetone and DMSO, and analyzed for viable chlorophyll *a* using fluorometric procedures (Welshmeyer 1994).

YSI 6000¹ recording data sondes were deployed approximately 0.3 m above the sediment surface in control and shredded sites 1-2 hr after mechanical shredding to monitor changes in turbidity and dissolved oxygen. Probes were pre-and post-calibrated using known standards and winkler titrations (American Public Health Association (APHA) 1992). The data sondes recorded measurements at 0.5-hr intervals for 1-2 weeks after mechanical shredding. The sonde deployed in the control station malfunctioned 1 week after deployment; data were not collected during the second week after mechanical shredding at this station.

Interstitial Water Analysis. Phosphorus (as SRP) and nitrogen (as NH₃-N) gradients in the sediment porewater were determined in situ at the control and shredded sites using sediment peepers (dialysis techniques). The acrylic peepers consisted of 12 chambers spaced at 2-cm intervals that were covered by a 0.2- μ m pore size dialysis membrane (Nucleopore Corp.) The procedures of Carignan (1984) and Shaw and Prepas (1989) were followed for the preparation, deployment, and retrieval of the peepers. Chambers were filled with nitrogen-purged distilled water and placed in a nitrogen-purged water bath prior to deployment to maintain anoxic conditions to determine transport to the stations. The peepers were gently pushed into the sediments so that up to three chambers (i.e., 6 cm into the sediment) were exposed to sediment pore water. Six replicate peepers were deployed in the control station and six replicate peepers were deployed in the experimental station approximately 18 hr after mechanical shredding. The peepers were allowed to equilibrate with the pore water for 14 days. Upon retrieval, samples were rapidly extracted from each chamber using syringes, immediately filtered through a 0.45- μ m membrane filter, and sealed in an airtight vial until analysis of SRP and NH₃-N.

Rates of Nutrient Release from the Sediments. Replicate (12) intact, sediment cores were collected at sampling stations located in the control and shredded areas 2 days prior to mechanical shredding for laboratory determination of rates of nitrogen and phosphorus release from the sediments.² The upper 10 cm of each sediment core was carefully extruded into a core liner (6.5-cm ID and 25-cm height). Lake water (300 mLs), collected from the sampling stations and filtered through a glass fiber filter (Gelman A/E), was siphoned onto the sediments. The sediment systems were sealed with rubber stoppers and incubated in a darkened environmental chamber at 20 °C for 1 week (the approximate temperature at the sampling stations). Six replicate sediment systems were subjected to an oxic environment, while another set of six replicate systems were subjected to an anoxic environment by gently bubbling the water column of each system with air or nitrogen, respectively. Water samples were collected daily from each system, filtered through a 0.45- μ m filter, and analyzed for SRP and NH₃-N using automated analytical techniques (see above). Rates of phosphorus (as SRP) and nitrogen (as NH₃-N) from the sediments were calculated as the linear

¹ Yellow Springs Instruments, Yellow Springs, OH.

² Wildco Wildlife KB sediment samplers with 6.5-cm inside diameter core liners were used.

change in mass in the overlying water divided by time and the area of the sediment incubation system.

Macrophyte Decomposition. Within hours of mechanical shredding, broken plant material was collected for determination of nutrient leaching and decomposition in mesh bags due to plant senescence. Excess water was drained from the shredded macrophytes (exclusively *T. natans*) and 100-g fresh mass aliquots were placed in 3-mm mesh bags. Macrophyte seeds were assumed to be resistant to decomposition and were not included in the bags. Extra macrophyte material was used to determine dry mass conversion factors. The bags containing plant material were deployed on racks at mid-depth in the water column (~0.3 m) of the shredded station 1 day after mechanical shredding. At intervals of 3, 6, 14, 27, and 55 days after initial deployment, five replicate bags were removed from the rack. The contents were dried at 70 °C for determination of tissue dry mass remaining. The dried material was then ground in a Wiley Mill, digested in a sulfuric acid-hydrogen peroxide matrix (Allen et al. 1974), and analyzed for tissue nitrogen and phosphorus using automated techniques (APHA 1992).

RESULTS AND DISCUSSION

Nutrient Gradients in the Sediment and Water Column. Before mechanical shredding (i.e., 24 July), total phosphorus concentrations were nearly homogeneous throughout the water column (range = 0.03 - 0.08 mg/L) and similar between the control and experimental station (Figures 2a and 2b). On 30 July (4 days after mechanical shredding), total phosphorus increased markedly in the lower third of the water column to >0.70 mg/L at the experimental station. In contrast, concentrations of total phosphorus were 0.1 mg/L near the bottom of the water column at the control station. In the experimental station, total phosphorus reached a maximum of 1.81 mg/L near the bottom on 2 August (7 days after mechanical shredding), then declined to 0.60 mg/L on 10 August (15 days after mechanical shredding). Total phosphorus was >0.50 mg/L at the 0.5-m depth in the experimental station on 10 August. Concentrations of total phosphorus also increased near the bottom of the water column in the control station during the study period. However, concentration increases were much lower relative to concentrations observed at the experimental station.

At the experimental station, SRP was <0.005 mg/L throughout the water column before mechanical shredding (24 July, Figures 2c and 2d). The control station exhibited slightly greater SRP concentrations near the surface than the experimental station on 24 July. However, concentrations were <0.005 mg/L below the 0.2-m depth in the control station on that date, similar to concentrations observed for the experimental station before mechanical shredding. Four days after mechanical shredding, the experimental station exhibited a water-column-wide increase in SRP. Greatest concentrations (0.015 mg/L) occurred near the bottom at the experimental station, similar to patterns observed for total P at the experimental station. Concentrations remained high relative to pretreatment SRP at the experimental station on 2 and 10 August. At the control station, SRP was nearly homogeneous and <0.01 mg/L throughout the water column during the study period. An exception to this pattern occurred on 10 August, as concentrations of SRP exceeded 0.01 mg/L near the bottom.

Total nitrogen concentrations exhibited a response similar to that of total phosphorus in the experimental station as a result of mechanical shredding. Total nitrogen was uniform throughout the water column at this station before mechanical shredding (Figures 3a and 3b). Between 30 July

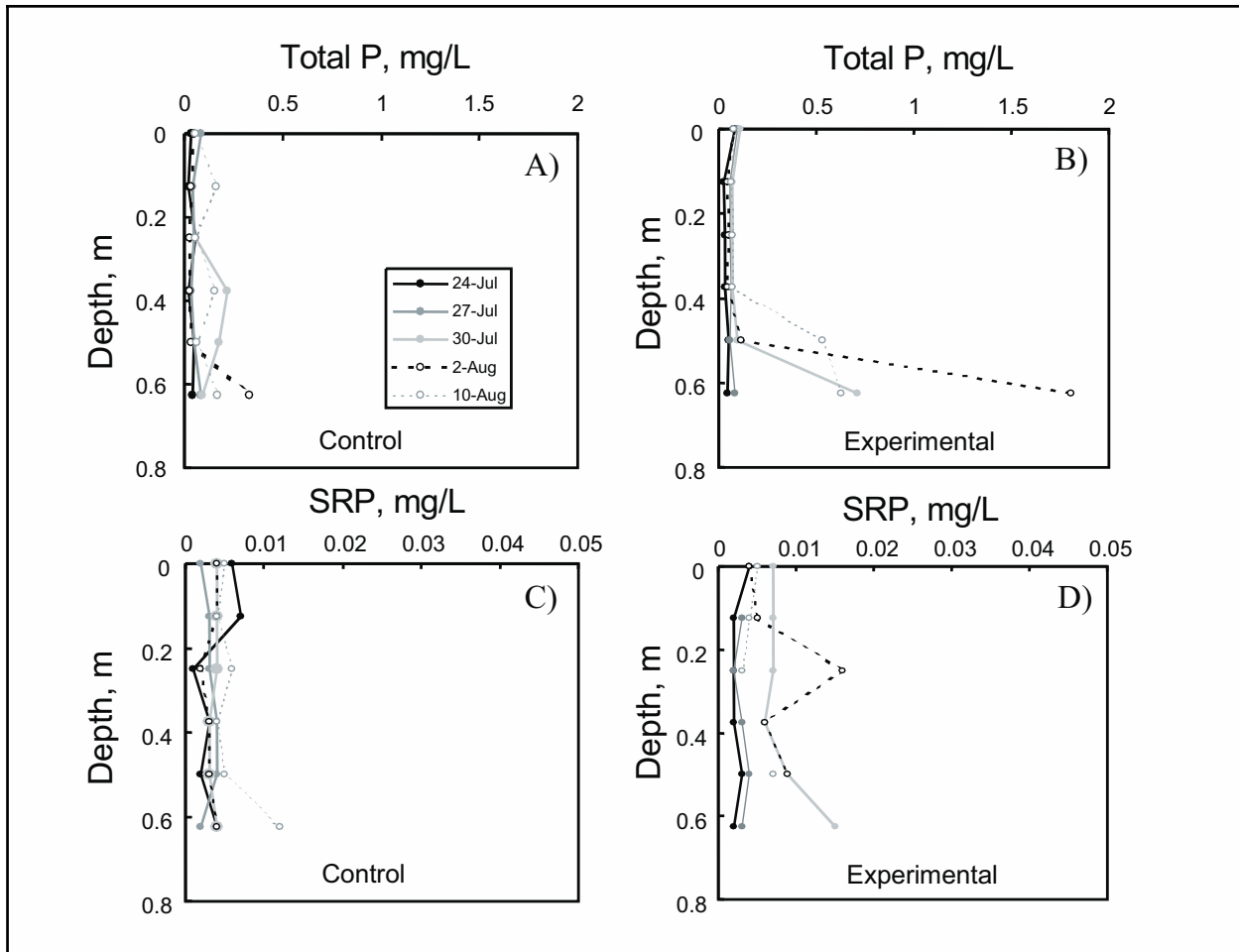


Figure 2. Variations in total phosphorus (TP) and soluble reactive phosphorus (SRP) in the water column at the control and experimental stations. Mechanical shredding occurred at the experimental site on 26 July 1999

and 10 August, concentrations of total nitrogen declined in the upper 0.5 m and increased substantially near the bottom, with concentrations exceeding 3.0 mg/L on 2 and 10 August. The control station exhibited a similar decline in total nitrogen near the surface between 24 and 30 July. However, total nitrogen concentrations were much lower in the bottom waters of the control station on 2 and 10 August, compared to concentrations in the experimental station on these dates. Ammonium-N exhibited minor increases in concentration near the bottom in the experimental station on 2 and 10 August, relative to both pretreatment patterns on 24 July and control levels on 2 and 10 August (Figures 3c and 3d).

Below the sediment-water interface, pore water SRP concentrations increased sharply to more than 1.5 mg/L between the 1- and 5-cm depth in both control and experimental stations (Figure 4; peepers represent an integrated pore water concentration between 27 July and 10 August). Above the sediment-water interface, pore water SRP was significantly greater in the experimental station than in the control station. These patterns of high SRP in the experimental station above the sediment-water interface reflected those patterns observed for total phosphorus and SRP in the water column.

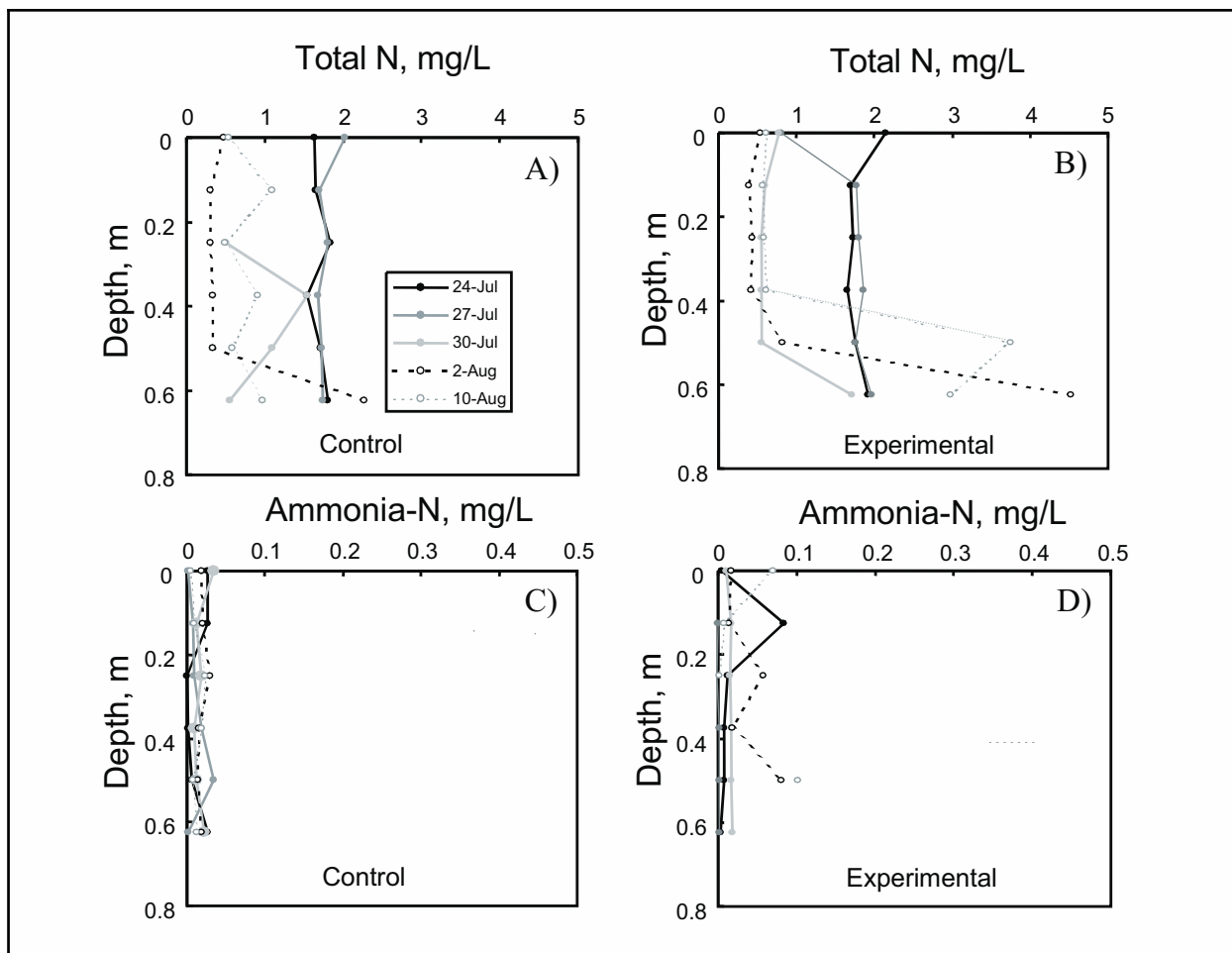


Figure 3. Variations in total nitrogen (TN) and ammonium-N ($\text{NH}_3\text{-N}$) in the water column at the control and experimental stations. Mechanical shredding occurred at the experimental site on 26 July 1999

Like SRP, marked gradients of increasing $\text{NH}_3\text{-N}$ concentrations were observed below the sediment-water interface. $\text{NH}_3\text{-N}$ was significantly greater in the experimental station than in the control station in the water column immediately above the sediment interface (Figure 5). Within the upper 5 cm of the sediment, pore water $\text{NH}_3\text{-N}$ concentrations were similar between the experimental and control station.

Chlorophyll. Before mechanical shredding, chlorophyll concentrations were three times higher at the experimental station than at the control station (Figure 6). The concentration (representing a mean over the entire water column) was approximately $5 \mu\text{g/L}$ in the control station and approximately $15 \mu\text{g/L}$ at the experimental station. Seven days after mechanical shredding, chlorophyll concentrations increased dramatically at the experimental station to $>35 \mu\text{g/L}$. In the control station, concentrations remained low and similar to those observed on 24 July.

Turbidity and Dissolved Oxygen. Immediately after mechanical shredding at the experimental station, turbidity exhibited a peak of $>50 \text{ NTU}$ due to sediment resuspension as an apparent result of the shredding machine (Figure 7). Between 26 July and 10 August, the experimental station

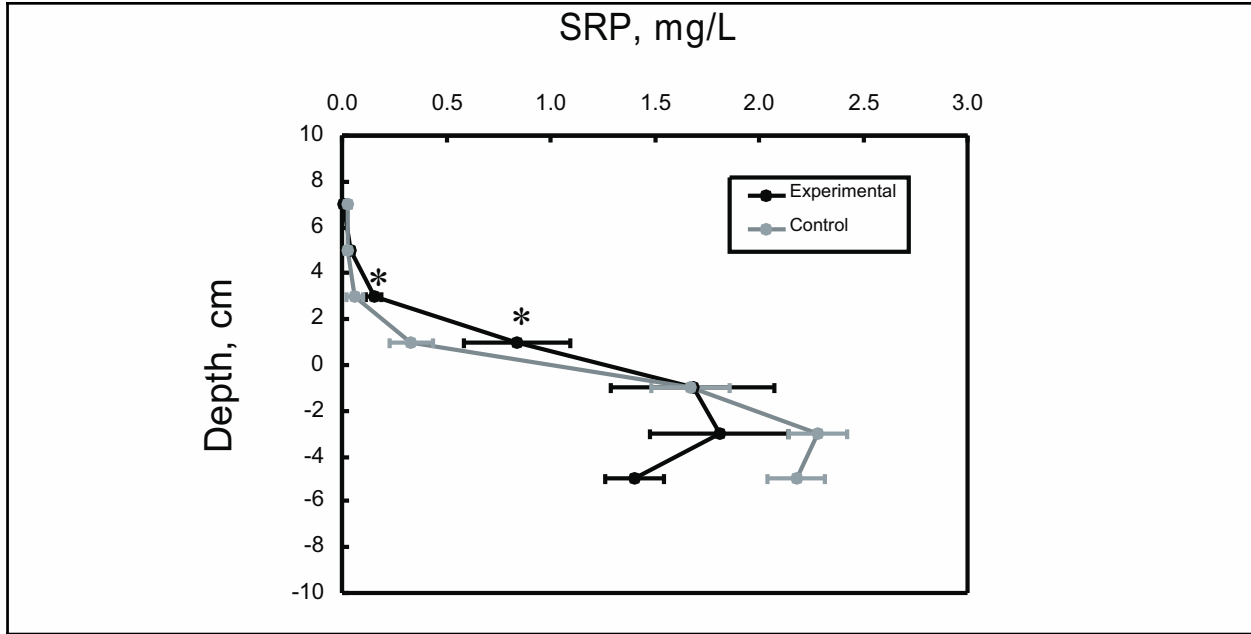


Figure 4. Mean (\pm 1 S.E.) variations in soluble reactive phosphorus (SRP) in the sediment pore water and overlying water for sediment peepers deployed at control and experimental stations. Concentrations represent the period 27 July through 2 August 1999. Mechanical shredding occurred at the experimental site on 26 July 1999. Asterisk indicates significant differences at $p < 0.05$ (t-test, SAS 1989)

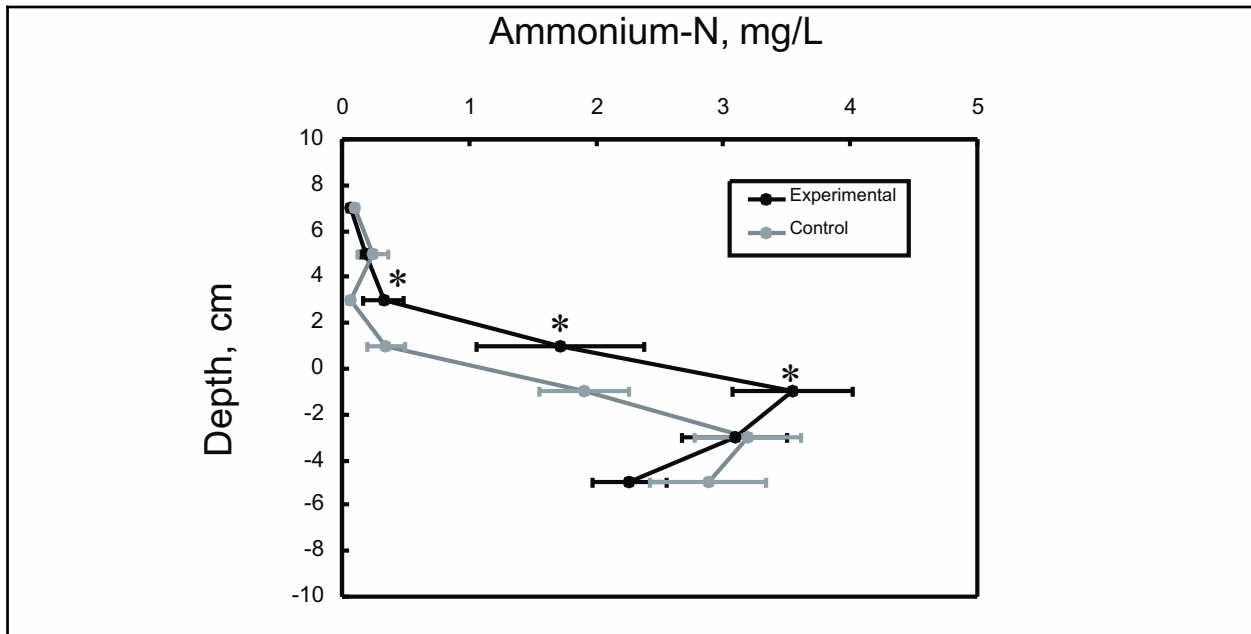


Figure 5. Mean (\pm 1 S.E.) variations in ammonium-N ($\text{NH}_3\text{-N}$) in the sediment pore water and overlying water for sediment peepers deployed at control and experimental stations. Concentrations represent the period 27 July through 2 August 1999. Mechanical shredding occurred at the experimental site on 26 July 1999. Asterisk indicates significant differences at $p < 0.05$ (t-test, SAS 1989)

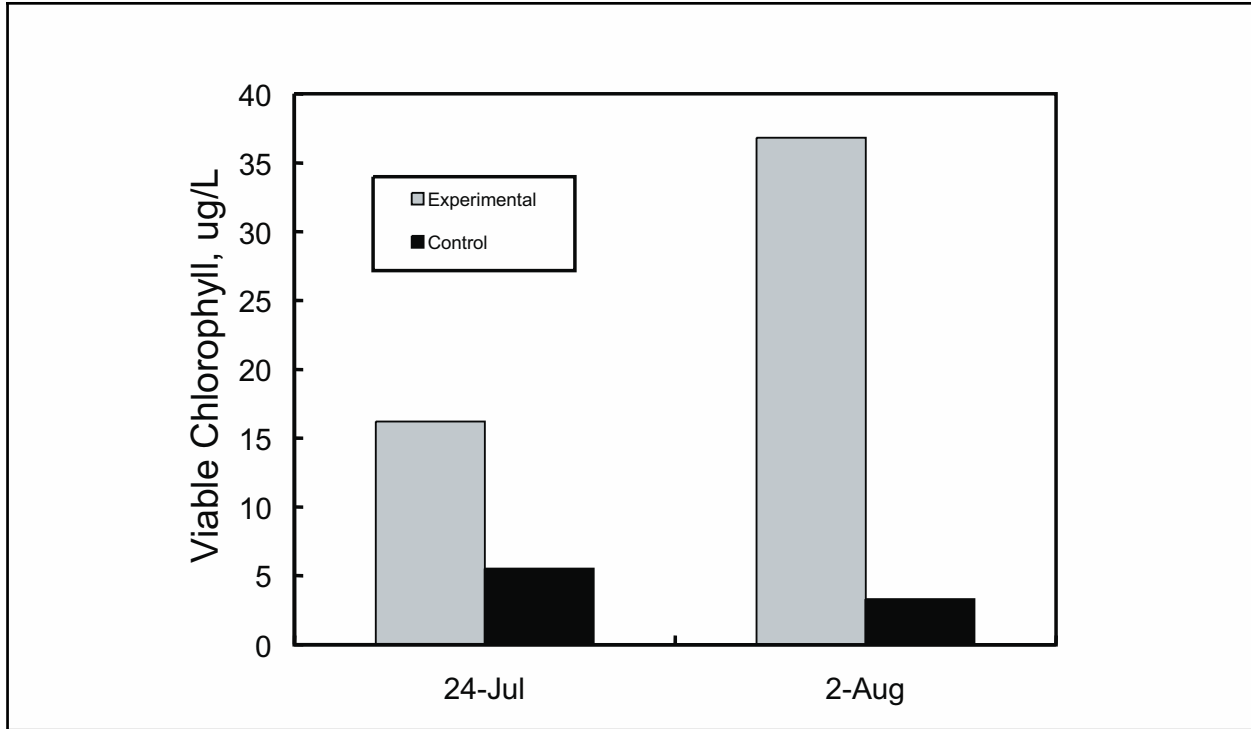


Figure 6. Changes in chlorophyll *a* at the control and experimental station on 24 July and 2 August 1999. Mechanical shredding occurred at the experimental site on 26 July 1999

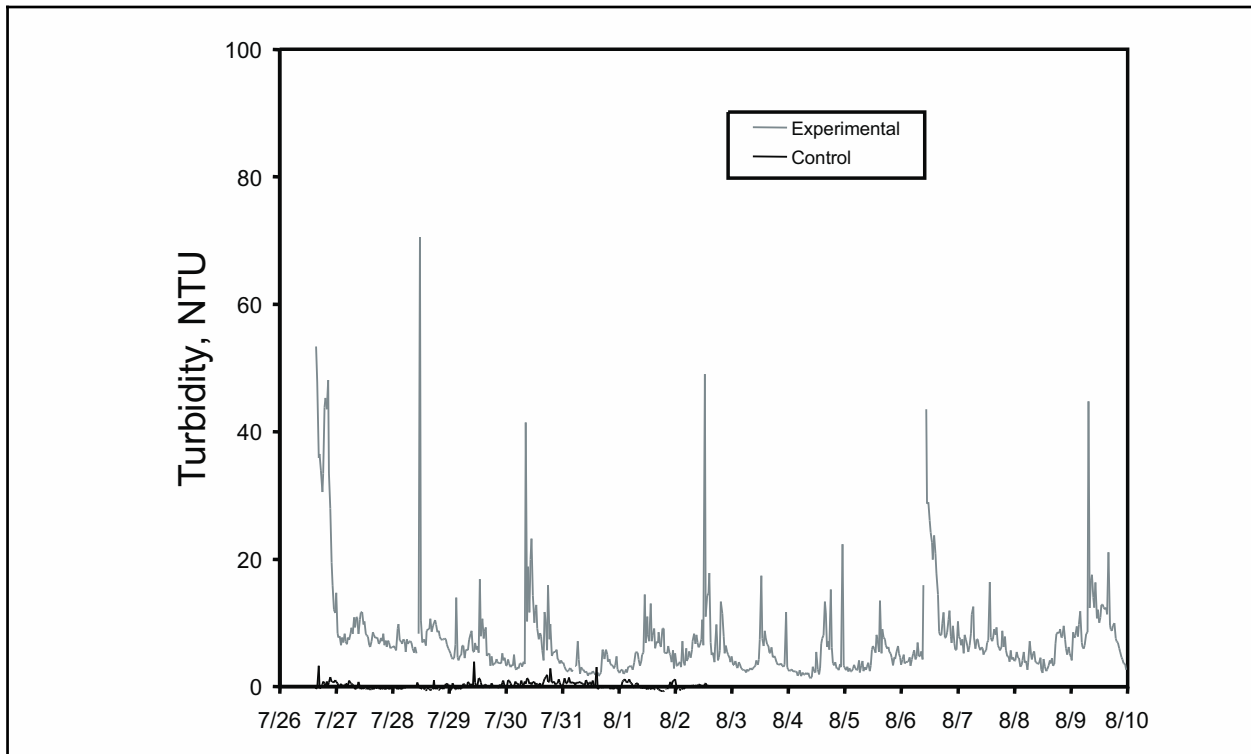


Figure 7. Variations in in situ turbidity at the control and experimental station after mechanical shredding of *T. natans* at the experimental site on 26 July 1999

exhibited markedly higher turbidity than the control station, coincident with disruption of the macrophyte canopy via shredding. Periodic peaks in turbidity in the experimental station throughout the study period may be attributed to wind-generated resuspension. In contrast, turbidity was near detection limits in the control station between 26 July and 2 August.

At the control station, dissolved oxygen was near zero during most of the study period (Figure 8). Minor peaks in the late afternoon were most likely due to net productivity by *T. natans*. At the experimental station, dissolved oxygen was near zero between 26 July and 1 August. However, concentrations increased to >2 mg/L in this station during the period 2 through 10 August, coincident with sedimentation of shredded material and exposure of the lake surface to wind-generated mixing. Unfortunately, dissolved oxygen measurements were not collected at the control station during that period due to instrument malfunction. High chlorophyll concentrations and presumably high algal productivity also likely contributed to dissolved oxygen increases in the experimental station between 26 July and 2 August.

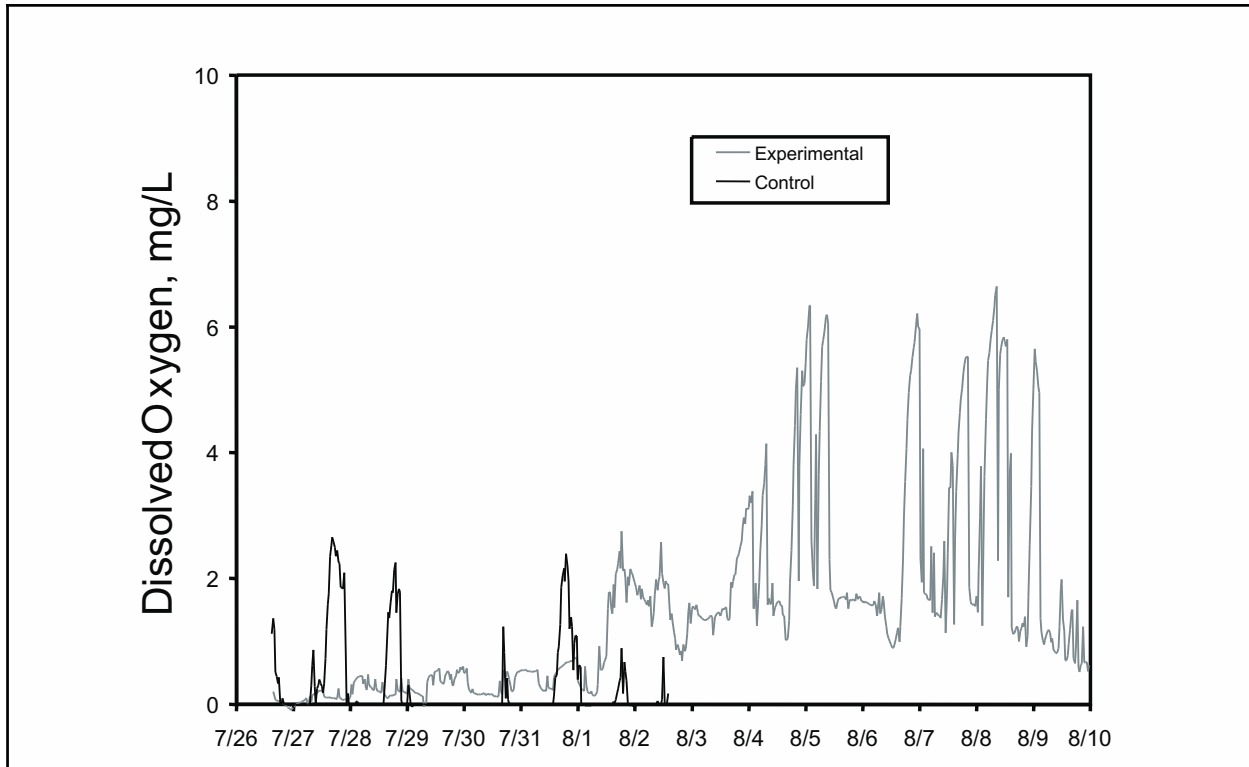


Figure 8. Variations in in situ dissolved oxygen at the control and experimental station after mechanical shredding of *T. natans* at the experimental site on 26 July 1999

Nutrient Recycling from Sediments and Decomposing Macrophytes. Rates of nitrogen and phosphorus release determined in the laboratory from sediments collected at the control and experimental stations were low relative (Table 1) to other eutrophic aquatic systems (Nürnberg et al. 1986; James, Barko, and Field 1995; 1996). In particular, rates of nitrogen and phosphorus release from sediments were negligible under oxic conditions for both stations (Table 1). Under anoxic conditions, modest rates of nitrogen and phosphorus release from sediments were observed (Table 1). Rates of phosphorus release from sediments under anoxic conditions were significantly

higher for sediments from the control station than from the experimental station (t-test; Statistical Analysis System (SAS) 1990). However, statistical differences between stations were not observed for rates of nitrogen release under anoxic conditions (t-test; SAS 1990).

Table 1				
Mean Rates (\pm S.E.) of Nitrogen and Phosphorus Release from Sediments Under Oxidic and Anoxic Conditions at Control and Experimental Locations in Lake Champlain				
Station	Nitrogen Release Rates mg m⁻² d⁻¹		Phosphorus Release Rates mg m⁻² d⁻¹	
	Oxic	Anoxic	Oxic	Anoxic
Control	N.D.	1.9 (1.4)	N.D.	0.8 (0.07)*
Experiment	N.D.	2.4 (1.3)	N.D.	0.3 (0.07)

* Indicates significant differences at $p < 0.05$ (t-test, SAS 1989).
 N.D. = not detected.

At the experimental station, large quantities of shredded *T. natans* material were visible on the surface of the lake shortly after the shredding process, due to the buoyant nature of its plant morphology. Shredded plant material was also observed on the lake surface by day 19 of treatment.¹ However, within 3 weeks the plants had completely settled from the surface. *T. natans* broke down rapidly in mesh bags after mechanical shredding, as nearly 70 percent of the initial dry mass was lost after only 14 days (Figure 9). Between 14 and 55 days of decomposition, dry mass in mesh bags remained low and approximately constant, indicating that only refractory organic material remained in the bags after 14 days of decomposition. Loss of nitrogen mass from decomposing *T. natans* was partially offset by tissue concentration increases during the decomposition process (Figure 9). This pattern may be attributed to some nitrogen accumulation on the material as microbial biomass (Triska, Sedell, and Buckley 1975). Nevertheless, only 58 percent of the initial nitrogen remained after 14 days of breakdown. Phosphorus loss from decomposing *T. natans* was very rapid, as 70 percent of the initial phosphorus mass was lost within 14 days (Figure 9).

Budgetary Analysis of Nitrogen and Phosphorus Sources. The mass of nitrogen and phosphorus that was potentially mobilized in the experimental station was estimated via sediment-water interactions and macrophyte decomposition over the 14-day period after mechanical shredding. To estimate sediment nutrient sources, the bottom waters at the experimental station were assumed anoxic (i.e., 2 mg/L dissolved oxygen) for the first approximately 7 days after shredding and oxic thereafter (Figure 8). Using rates of nitrogen and phosphorus release from sediments under oxic and anoxic conditions (Table 1) and an area of 100 ha (i.e., area that was mechanically shredded), approximately 200 g nitrogen and 20 g phosphorus were mobilized from the sediments over a 14-day period. In contrast, decomposition of *T. natans* after mechanical shredding resulted in mobilization of 40,000 g of nitrogen and 10,000 g of phosphorus at the experimental station over the same time period.

¹ Personal Communication, 2000, Ann Bove, Vermont Department of Environmental Conservation.

Conclusions and Implications of Mechanical Shredding on Water Quality in Lake Champlain. As an apparent result of dense surface canopies in *T. natans* beds, dissolved oxygen concentrations were near zero in the bottom waters on a diel time scale during the study period. Factors potentially contributing to low dissolved oxygen included suppression of reaeration from the atmosphere (i.e., mixing) by the surface canopy, the development of light-limiting conditions below the canopy for photosynthesis and production of oxygen by other plant and algal species, and dissolved oxygen demand via respiration of *T. natans* and benthic microbial organisms. Others (James and Barko 1991; James, Barko, and Field 1996) have observed low dissolved oxygen conditions in dense macrophyte beds.

Mechanical shredding of *T. natans* coincided with improved dissolved oxygen conditions in the bottom waters of the experimental station, as dissolved oxygen concentrations increased to more than 2 mg/L 7 days after shredding. This observation was unusual since macrophyte biomass was high (7-8 kg F.W./m²)¹ at the time of mechanical shredding and, thus, decomposition of this material represented a potentially large demand on oxygen stores at the experimental station, relative to the control station. However, increases in dissolved oxygen at the experimental station were associated with disruption of the surface canopy and a large increase in chlorophyll *a* concentration. These patterns suggested that oxygen demands created by decomposing macrophytes were offset by enhanced productivity by the algal community and reaeration from the atmosphere via wave activity and mixing processes.

Turbidity levels increased dramatically over a 14-day period in the experimental station after mechanical shredding, relative to the control station, suggesting some sediment resuspension due to increased wave activity. In particular, macrophytes can reduce sediment resuspension in shallow systems by dampening wave activity and redirecting water currents (Dieter 1990, Losee and Wetzel 1993, James and Barko 1994). Mechanical shredding of the canopy probably exposed the lake surface directly to wind effects, which promoted more frequent sediment resuspension in the experimental station. In contrast, high surface canopy biomass in the control station inhibited sediment resuspension and promoted sedimentation of particles, thereby resulting in negligible turbidity.

Mechanical shredding of *T. natans* resulted in the buildup of nitrogen and phosphorus in the water column of the experimental station. Concentration increases were most pronounced in the lower half of the water column of the experimental station after shredding. Clearly, the source of these nutrient increases in the water column was decomposing macrophyte material, based on a budgetary comparison of nutrient mobilization via decomposing macrophytes and the sediments. Gradients of high total nitrogen and phosphorus in the bottom waters of the experimental station after shredding perhaps reflected some settling of fragmented macrophyte material.

Based on decomposition of *T. natans* in mesh bags, loss of phosphorus from tissue was rapid during the first 6 days and could represent a substantial source of phosphorus to the water column. Although SRP increased in concentration in the experimental station compared to the control station over this period, a pulse of high SRP shortly after shredding was not observed. However, the

¹ Personal Communication, 2000, R. Michael Stewart, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

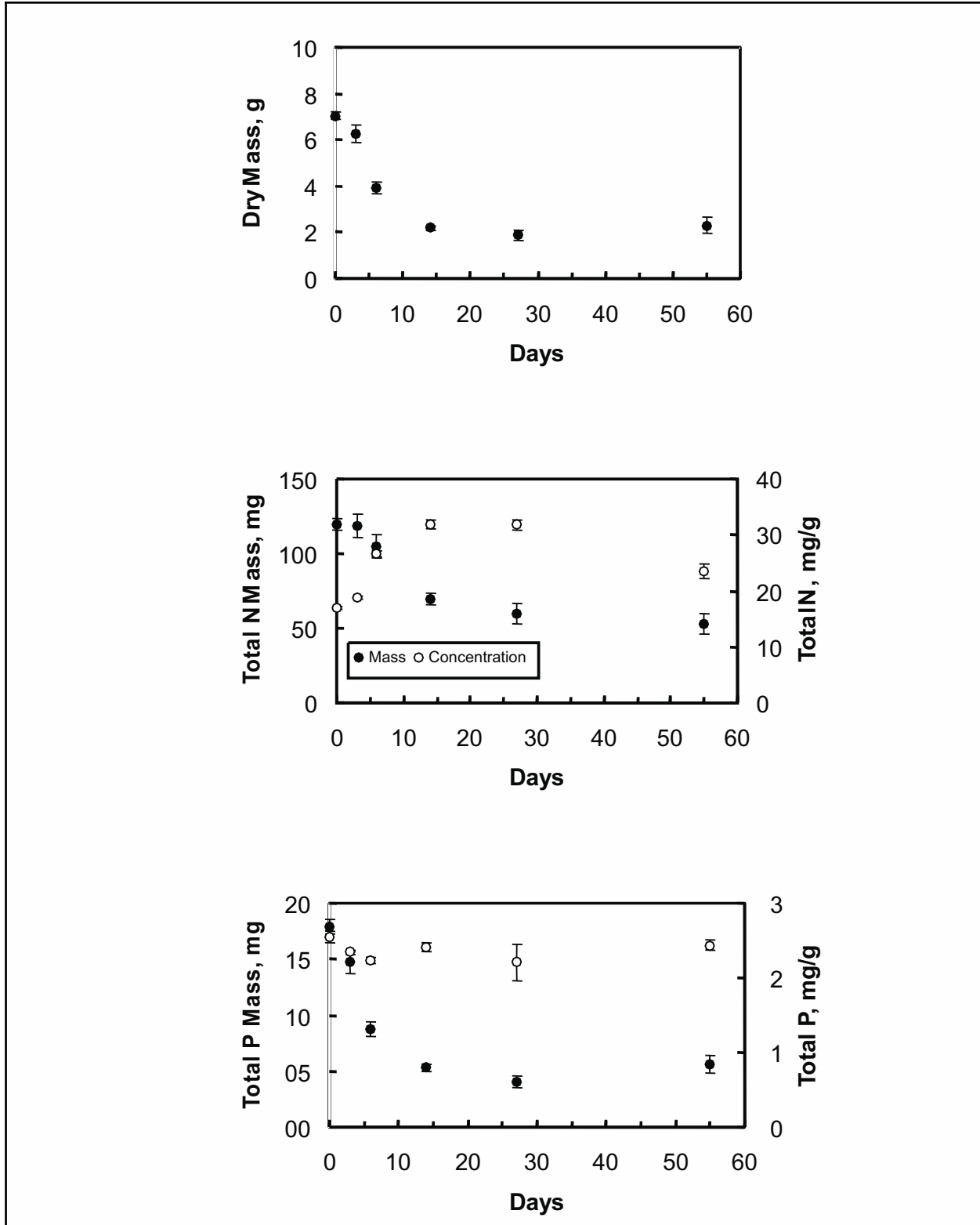


Figure 9. Variations in dry mass, nitrogen and phosphorus mass, and nitrogen and phosphorus concentration as a function of time for decomposing *T. natans* contained in mesh bags. Mesh bags were deployed at the experimental station approximately 1 day after mechanical shredding

chlorophyll concentration increased markedly in the experimental station after mechanical shredding, suggesting uptake of SRP by algae for growth. Flushing and transport of SRP and other nutrients downstream may have also occurred, thus diluting concentrations via water exchange in the experimental station.

Results suggest that mechanical shredding resulted in both positive and negative effects on water quality in Lake Champlain. Disruption of the surface canopy of *T. natans* was associated with an increase in dissolved oxygen concentrations. However, decomposition of *T. natans* resulted in nutrient mobilization and an increase in algal biomass to high levels of chlorophyll. These water quality effects need to be considered in the development of macrophyte management plans for controlling *T. natans* via mechanical shredding.

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