IDENTIFYING SEDIMENT NUTRIENTS THAT FURTHER CHARACTERIZE THE HABITAT ASSOCIATED WITH THE ENDANGERED TEXAS WILDRICE (*ZIZANIA TEXANA* HITCH.)

THESIS

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By

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ABSTRACT

Interstitial water samplers (peepers) were used to examine porewater nutrients associated with a particular stand of the endangered aquatic macrophyte, Texas wildrice (*Zizania texana* Hitchcock), in the San Marcos River in June, August, and November 1998. Peepers were oriented vertically down into the sediments to capture water in discrete chambers at 2.5 cm intervals from approximately 15 cm above the sediment-water interface and to a depth of 15 cm into the sediments. They were deployed under the leaf blades (inside the stand) and adjacent to or upstream of the stand (outside the stand). Samples were analyzed for NO_3-N and soluble reactive phosphorus (SRP). Water column concentrations were around 1.0 mg L^{-1} NO_3-N and 10 μg L^{-1} SRP. Porewater concentrations were <0.4 mg L^{-1} NO_3-N and between 10 and 58 μg L^{-1} SRP. Porewater phosphorus concentrations were highly patchy indicating a dynamic

sediment structure in the river channel. Significant differences between nutrient concentrations were predominately observed between the water column and porewater and less common between inside and outside the stand. A nutrient limitation experiment using low P (500 μg L^{-1}), high P (1000 μg L^{-1}), and N+P (1.5 mg L^{-1} N + 500 μg L^{-1}) showed a slight increase in plant mass between P treatments ($p<0.10$); however, the relationship between plant mass and enrichment concentration was weak ($r=0.44$). Only a slight effect on plant mass was observed in the N-enriched plants ($p=0.08$), but not leaf lengths. The lowest r:s ratio was observed in the N+P enrichment.

INTRODUCTION

Sediment nutrients

Uptake of nutrients such as nitrogen and phosphorus have received a great deal of attention from aquatic plant researchers. Generally, it is accepted that nutrients such as N, P, Fe, and Mn are taken up from the sediments by rooted macrophytes rather than from the water column (summarized in Barko et al. 1991). However, nutrient contributions of sediments and water column greatly depend on several factors, including sediment composition (Barko and Smart 1986), trophic status of the water column (Robach et al. 1995), nutrient availability within the sediments (McCreary et al. 1991), and plant growth habit (Denny 1972),

Barko and Smart (1986) found that increasing organic matter actually hinders growth of *Hydrilla verticillata* (L.f.) Royle and *Myriophyllum spicatum* L. due to decreased density of the sediments. Characteristic of low density sediments is the increased distance nutrients must diffuse, which slows uptake of nutrients by the roots.

Laboratory research by Carignan and Kalff (1980) used ^{32}P to determine that the sediments were the primary source of nutrient uptake for three aquatic macrophytes.

Some macrophytes, such as *Potamogeton americanus,* are capable of oxidizing adjacent sediments, lending to the conversion of the NH_4 to NO_3 and ultimately to N_2 gas. Such losses of sediment N can be advantageous under potentially competitive situations such as with the invasive exotic, *Hydrilla verticillata* (L.f.) Royle (McCreary et al. 1991).

Carpenter (1981) has shown that stands of aquatic macrophytes can trap dissolved and particulate matter within plant stands, thereby increasing sedimentation. This increase in sedimentation may replenish nutrient losses resulting from plant uptake (Barko et al. 1991).

San Marcos Springs

The San Marcos Springs are one of the two largest spring systems in Texas. The springs arise from the Edwards Aquifer whose recharge zone is rich in karst topography (US Fish and Wildlife 1996) (Figure 1). The springs were dammed in 1849, resulting in Spring Lake, the headwaters of the San Marcos River (Brune 1981). The water in the river and lake are characteristically clear with a near constant average temperature of 22°C and pH of 6.9-7.8 (US Fish and Wildlife 1996). Although flows can vary, the springs have never ceased flowing (Ogden et al. 1986). The San Marcos River supports a diverse community of both native and exotic macrophytes. Lemke (1989) documented a comprehensive list of macrophytes found in the river. Of the 31 species listed, 23

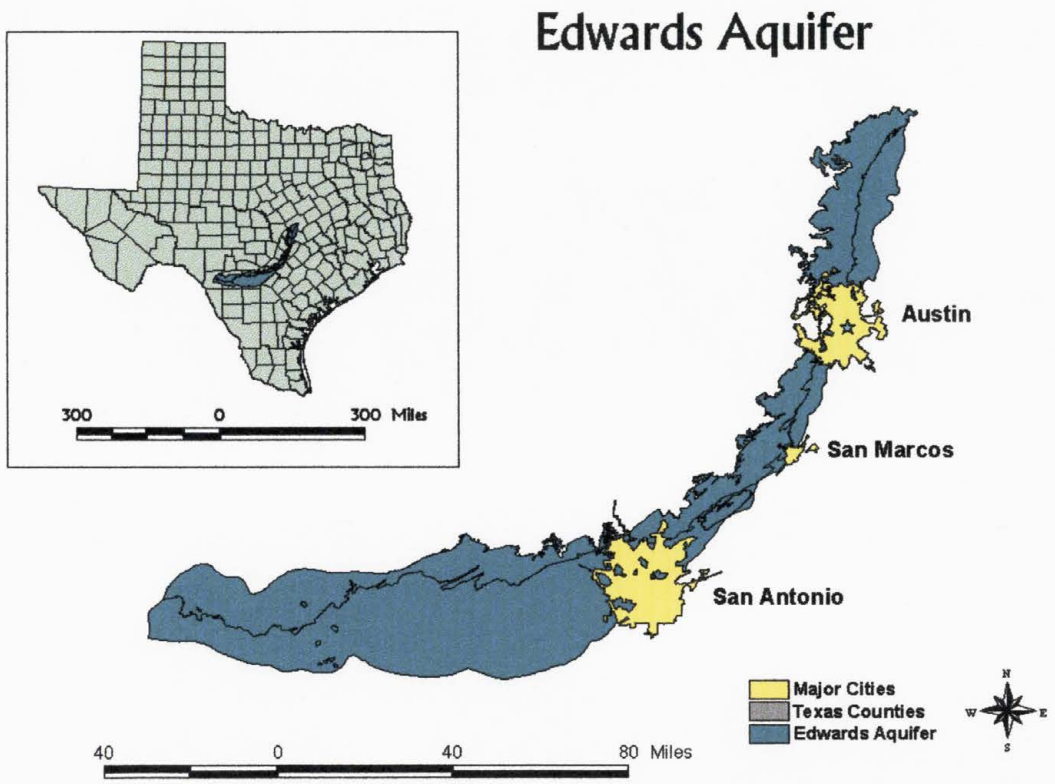

Figure 1. The Edwards Aquifer region of Texas.

were native to the San Marcos River, the most common being *Potamogeton illinoensis* Morong and *Sagittaria platyphylla* Engelmn. The most common exotic species found were *Hydrilla verticillata* (L.f.) Royle, *Egeria densa* Planch., *Eichhornia crassipes* (Mart.) Solms, *Myriophyllum brasiliense* Camb., and *M. spicatum* L.

The endangered *Zizania texana* Hitchc., (Texas wildrice), is a perennial, emergent macrophyte in the family Poaceae. It produces submersed leaves 1-2 m long and may form emergent leaves and flowers in reduced currents (US Fish and Wildlife Service 1995). It has experienced a population decline in the San Marcos River since 1940 (Emery 1967). Formerly, mowing, plant collecting, and pollution contributed to the reduction of Texas wildrice (Emery 1967). Current threats to the species include competition and damage by exotic species, predation by waterfowl and nutria (*Myocaster coypus*), and recreational activities (US Fish and Wildlife Service 1995).

Poole and Bowles (in press) characterized the sediment of Texas wildrice transects versus non-Texas wildrice transects throughout the San Marcos River. They found insignificant differences in water column physio-chemical parameters (pH, dissolved oxygen, specific conductance, and temperature) between the Texas wildrice and non-Texas wildrice transects. Composition of the sediments was quite different between transects. In the Texas wildrice transects, sand comprised 69%, silt 12%, and clay 19% of the sediment. In the non-Texas wildrice, transects sand comprised 31%, silt 31%, and clay 37% of the sediment sampled. Water velocity through rice transects ranged from 0.29 to 0.63 m s^{-1}

while non-Texas wildrice transects ranged from 0.05 to 0.21 m s^{-1}. Sediment nutrients were reported as 12.67 and 6.51 mg L^{-1} total nitrogen and 73.67 and 85.53 mg L^{-1} total phosphorus for Texas wildrice and non-Texas wildrice transects, respectively.

When grown on sandy clay loam, Texas wildrice exhibited the lowest root to shoot ratio compared to growth on clay and gravel. This may be due to the compacted nature of the clay sediments and low nutrient availability of the gravel sediments compared to the intermediate texture and nutrient composition of the sandy clay loam (Power 1996b). Stem density was greatest in sandy clay sediments compared with gravel sediments in currents ranging from 0.40-0.49 m s^{-1} (Power 1996a).

The San Marcos River has been shown to be strongly P limited for phytoplankton and periphyton (Groeger et al. 1997). Generally, N is more limiting to macrophyte growth than P, largely due to the decreased availability of exchangeable N in the sediments compared to P (Barko et al. 1991). A nutrient limitation experiment on Texas wildrice indicated N was the primary nutrient limiting its growth under experimental conditions based on increased biomass and low r:s ratios in the highest N treatment (Power, unpublished data).

The US Fish and Wildlife Service describes in detail the recovery criteria as well as other factors associated with Texas wildrice (1995). To improve the status of Texas wildrice from endangered, there must be at least 11,930 m^2 aerial coverage of self-sustaining Texas wildrice in its historic range. In 1994, aerial coverage was 1,500 m^2 (USFWS 1995). To elucidate the factors that may

increase this single population, further research is required. By defining nutrients available in sediments associated with Texas wildrice and determining the nutrients limiting its growth, information contributing to the preservation of Texas wildrice may be provided. The objectives of this research were 1) to characterize the sediment nutrient profile associated with a particular stand of wildrice and 2) to determine the primary nutrient(s) limiting its growth in a controlled setting.

METHODS AND MATERIALS

Study Site

A stand of Texas wildrice (≈1 x 2 m) approximately 15 m upstream from the outfall of the A.E. Wood State Fish Hatchery was selected due to absence of neighboring vegetation, accessibility, and decreased likelihood of vandalism (Figure 2). Water depth ranged from 0.5 to 1.2 m for the majority of the *in situ* study. Leaf blades were completely submerged throughout the study and plants did not produce emergent flowers.

On 17 October 1998, a 500-year flood event caused water in the San Marcos River to peak at 21.29 feet at the USGS gaging station on the San Marcos River (08170500) and discharge water at a maximum of 21,500 cubic feet per second (http://tx.usgs.gov). Deposition of sediments from the watershed almost completely buried the stand of Texas wildrice used in this experiment as well as surrounding vegetation. Only a few small blades of Texas wildrice were visible after flooding.

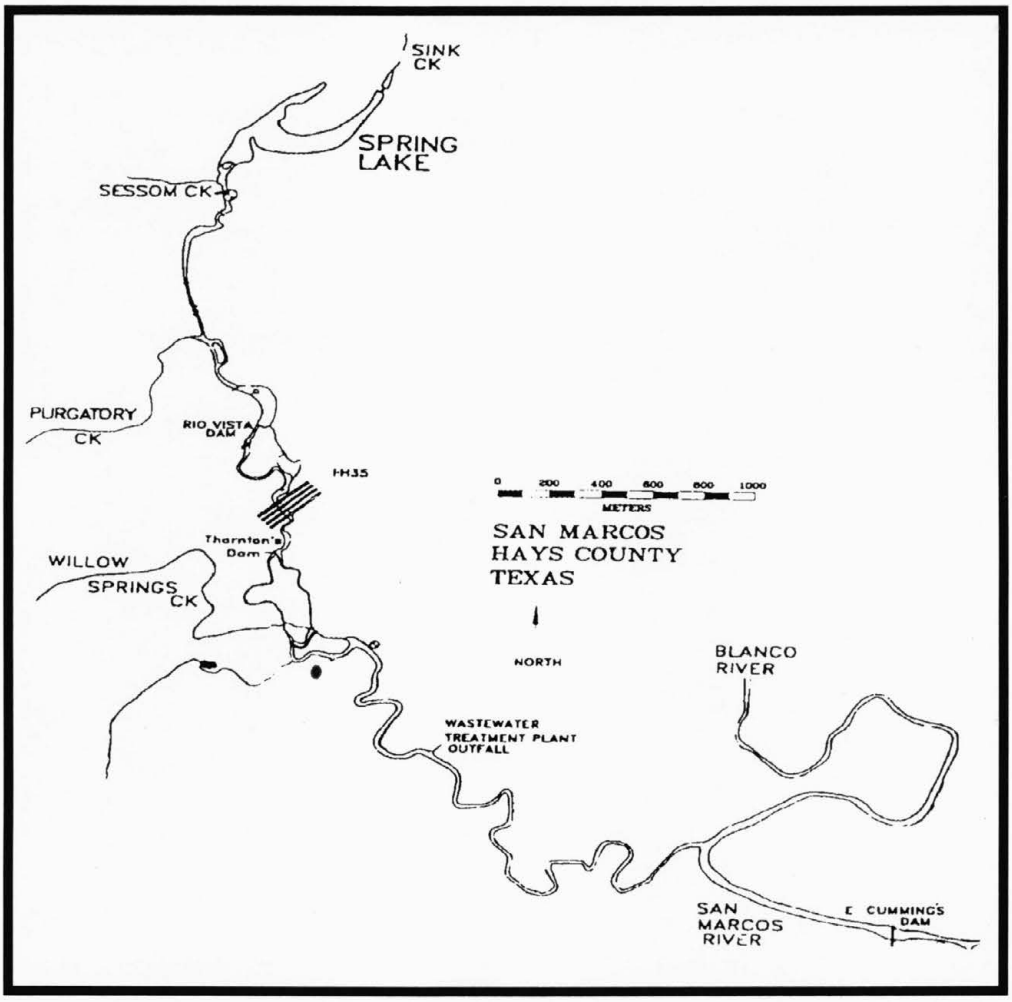

Figure 2. San Marcos River from its headwaters to the confluence with the Blanco River. The stand of Texas wildrice used for the nutrient profiles is indicated by a solid black circle (•). *Map courtesy of US Fish and Wildlife Service.*

Interstitial nutrient determination

Plexiglas interstitial water samplers (peepers) similar to those described by Eakin and Barko (1995) were used to vertically capture water in twelve discrete chambers distributed aproximately 2.5 cm apart and inserted about half way into the sediments (Figure 3). Peepers were deployed on 14 June, 17 August, and 2 November 1998 at the same site (Figure 2). On the first two

sampling occasions, four peepers were deployed under the leaf blades on the downstream side of the stand (inside the stand) and four were deployed adjacent to or upstream of the stand and free of vegetation (outside the stand). In November, peepers were only placed outside the stand because sediment deposition the previous month buried the stand used in this experiment. Henceforth, November data will be refered to as "outside" the stand.

Each peeper had 12 collection chambers capable of collecting approximately 22 ml of water. Each chamber was filled with N_2-sparged water before insertion to reduce the introduction of oxygen into the sediment layers and prevent the alteration of redox conditions. A 2.0 μm Nuclepore® track-etch membrane (Coring Separation) was placed over the cells and held in place by a plastic cover with openings mirroring those of the peepers. Plastic screws were used to hold the cover in place. Peepers were inserted approximately half way into the sediments such that water would diffuse from the water column and interstitial spaces of the sediments into the collection chambers. Peepers remained in place for approximately ten days, after which time they were removed from the sediments and water was pulled from each cell with a syringe, filtered, transferred to acid washed bottles, and stored on ice until analysis within 48 hours.

Samples were analyzed for soluble reactive phosphorus (SRP) colorimetrically following Standard Methods (APHA 1995) using the ascorbic acid technique and analyzed on a Shimadzu UV-VIS spectrophotometer. Nitrate-nitrogen was determined by high pressure liquid chromotrography

(HPLC), also following Standard Methods (APHA 1995). Components included a Waters model 510 pump, model 486 UV absorbance detector, and a model 746 data module. Ammonium-nitrogen was determined by the known addition method on an Orion Research EA 940 Expandable Ion Analyzer.

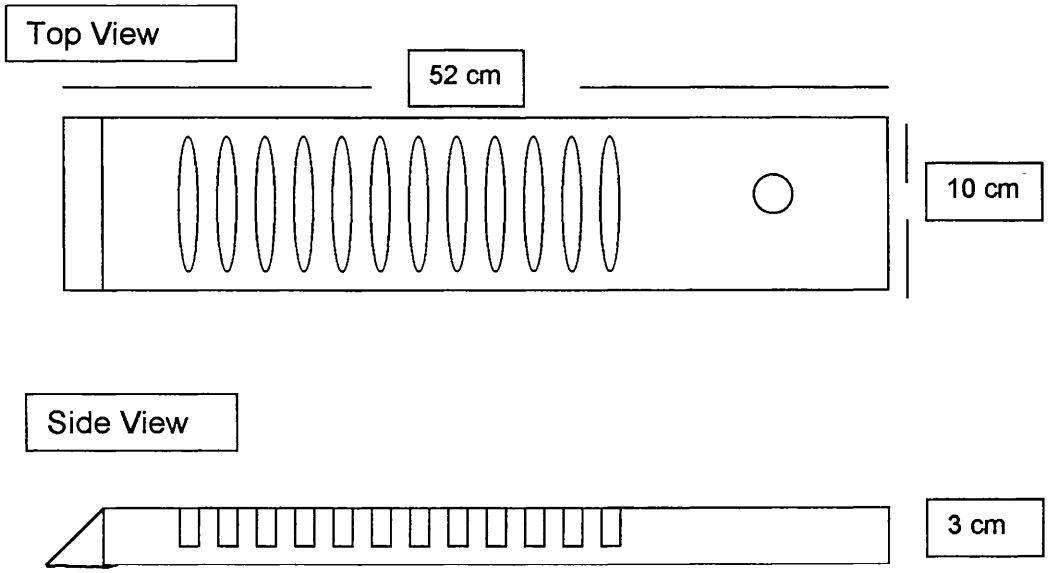

Figure 3. Interstitial water sampler ("peeper").

Sediment analysis

Sediment grab samples were taken in August inside and outside the stand and in November outside the stand. Sediments were dried for 24 hours at 80°C and sieved through a #10 sieve to separate gravel (>2.0mm) from soil (<2.0mm). Percent organic matter of the soil was determined by combustion at 550°C until a constant weight was attained.

Tissue nutrients

Submersed and emergent leaves from adult plants and newly germinated shoots from the conservation population of Texas wildrice on the Southwest Texas State University campus were obtained. Plants were dried at 80°C, ground, and approximately 0.25 g of dried plant material was digested in a sulfuric acid-hydrogen peroxide solution (Allen et al. 1974). Ammonia-nitrogen was determined by an Alpkem RFA 300 and ortho-P was determined by a Milton Roy Co. Spectronic 20 D spectrophotometer following Allen et al. (1974).

Nutrient limitation experiment

An experiment was conducted to determine the primary nutrient(s) potentially limiting the growth of Texas wildrice. Plants were grown in a cement channel on the SWT campus in an exclosure constructed of polyvinyl chloride (PVC) pipe and 1 cm^2 mesh hardware cloth to hinder crayfish predation. Water flowing through the channel arose from an artesian well from the Edwards Aquifer.

Seedlings were grown in sand enriched with varying concentrations of P (as KH_2PO_4), N (as $Na(NH_4)HPO_4$) and N+P. Treatments of low P (500 $\mu g\ L^{-1}$), high P (1000 $\mu g\ L^{-1}$) and N+P (500 $\mu g\ L^{-1}$ P + 1.5 mg L^{-1} N) were made by combining nutrients and distilled water with dry sand. Distilled water was also used in the unamended sand (control). Each treatment began with five to seven replicates randomly placed in the PVC exclosure. However, predation and

dense epiphyte growth reduced some replicates to four per treatment. Maximum leaf length was measured on six occasions from 16 December 1998 to 8 February 1999 after which time plants were separated into roots and shoots, dried at 80°C and weighed.

Analysis

A two-way analysis of variance (ANOVA) was used to detect significant differences in nutrient concentrations (NO_3-N and SRP) through the sediment profile as well as between inside/outside the stand in June and August. Because the plant stand was not present in November, a one-way ANOVA was used to determine significant differences in nutrient concentrations in the sediment profile.

ANOVA was used to determine significant differences between mean porewater and mean water column concentrations of SRP and NO_3 inside and outside the stand in June and August. A Student's t-test was used to determine significant differences between mean porewater and mean water column SRP and NO_3 in November.

Differences in percent organic matter in August and November were determined with a t-test. Increases in leaf lengths and root to shoot (r:s) ratios in the nutrient limitation experiment were analyzed with ANOVA. Significant differences in plant mass (mg dry wt.) between P enriched plants (control, low P and high P) were analyzed with ANOVA while differences in N enriched plants (N+P and low P) were analyzed with a t-test.

RESULTS

Interstitial nutrients

Nitrate

Patterns in NO_3 concentrations in the water column and sediment porewater were similar for all sampling events. Concentrations ranged from 0.9 to 1.3 mg L^{-1} NO_3-N in the water column, were somewhat less at the sediment-water interface (represented by "0 cm" in each figure), and were lowest in the sediments, often less than the detection limit (0.02 mg L^{-1}) (Figures 4, 5, and 6). During all months sampled, variation in nutrient concentration was high in the sediment porewater.

The greatest change in NO_3 concentration occurred between the sediment-water interface and approximately 3 cm below the sediment-water interface. Outside the stand in June, NO_3 concentrations decreased rapidly below the interface and continued to decrease to < 0.4 mg L^{-1} NO_3-N (Figure 4). Inside the stand, concentrations were slightly higher in the porewater than outside the stand. Nitrate-nitrogen was < 0.4 mg L^{-1} NO_3-N below the sediment-water interface. Slight variation in NO_3 was found between inside and outside the stand (ANOVA, $p<0.10$), but NO_3 concentrations were more influenced by

depth than location (inside/outside) ($p<0.01$).

Unlike June, August NO_3 concentrations decreased near the sediment-water interface inside the stand and decreased outside the stand approximately 5 cm into the sediments. Between 5 and 25 cm, NO_3 was < 0.2 mg L^{-1} NO_3-N in the sediment profile (Figure 5). Nitrates in August showed no relationship between concentration and inside/outside the stand; however, there was a significant inverse relationship between depth and NO_3 concentrations, as depth increased, NO_3 decreased (ANOVA, $p=0.002$).

In November, where only an "outside the stand" determination was possible, NO_3 decreased slowly from the sediment-water interface to < 0.4 mg L^{-1} NO_3-N below 5 cm in the sediments (Figure 6). Increasing depth also had significant effects on the decreasing NO_3 concentrations (ANOVA, $p=0.02$).

For June, August, and November there were no significant differences found between mean NO_3 concentrations inside and outside the stand in either the water column or the porewater (Figure 7). Additionally, there were no interactions found between location (inside/outside) or between mean nutrient concentrations (water column/porewater). In all months, there were significant differences found between mean NO_3 concentrations in the water column and porewater ($p<0.001$).

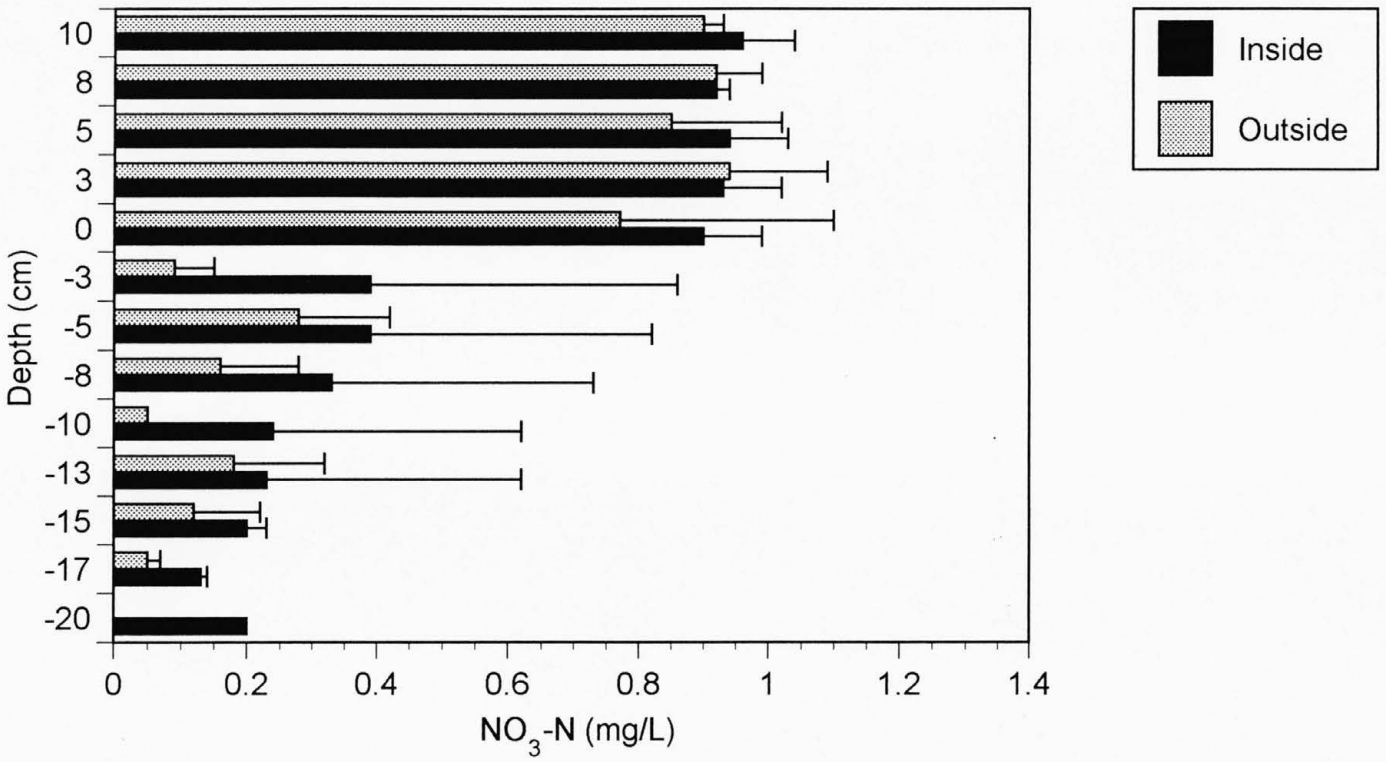

Figure 4. June nitrate concentrations inside and outside the stand of Texas wildrice. Black bars indicate mean concentrations of nitrate (mg/L) inside the stand at each depth while gray bars indicate concentrations outside. "0 cm" indicates the sediment-water interface. Error bars are +/- SD.

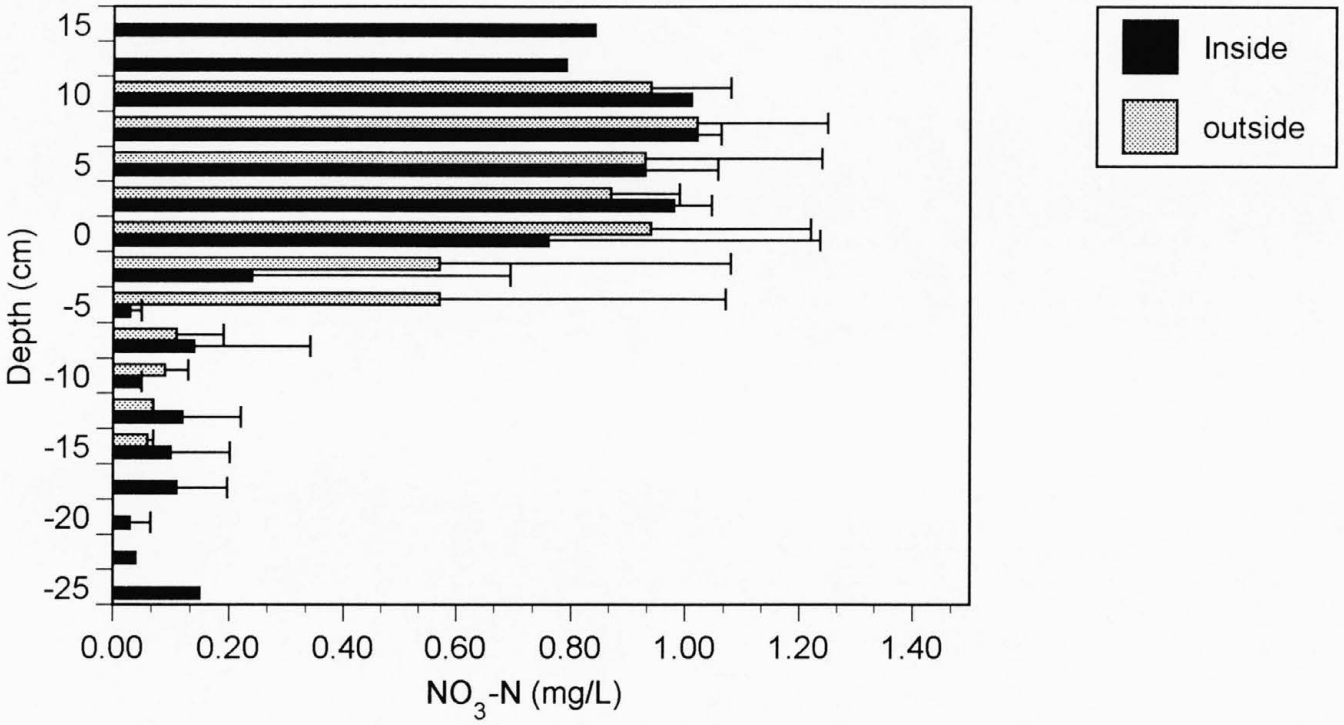

Figure 5. August nitrate concentrations inside and outside the stand of Texas wildrice. Black bars indicate mean concentrations of nitrate (mg/L) inside the stand at each depth while gray bars indicate concentrations outside. "0 cm" indicates the sediment-water interface. Error bars are +/- SD.

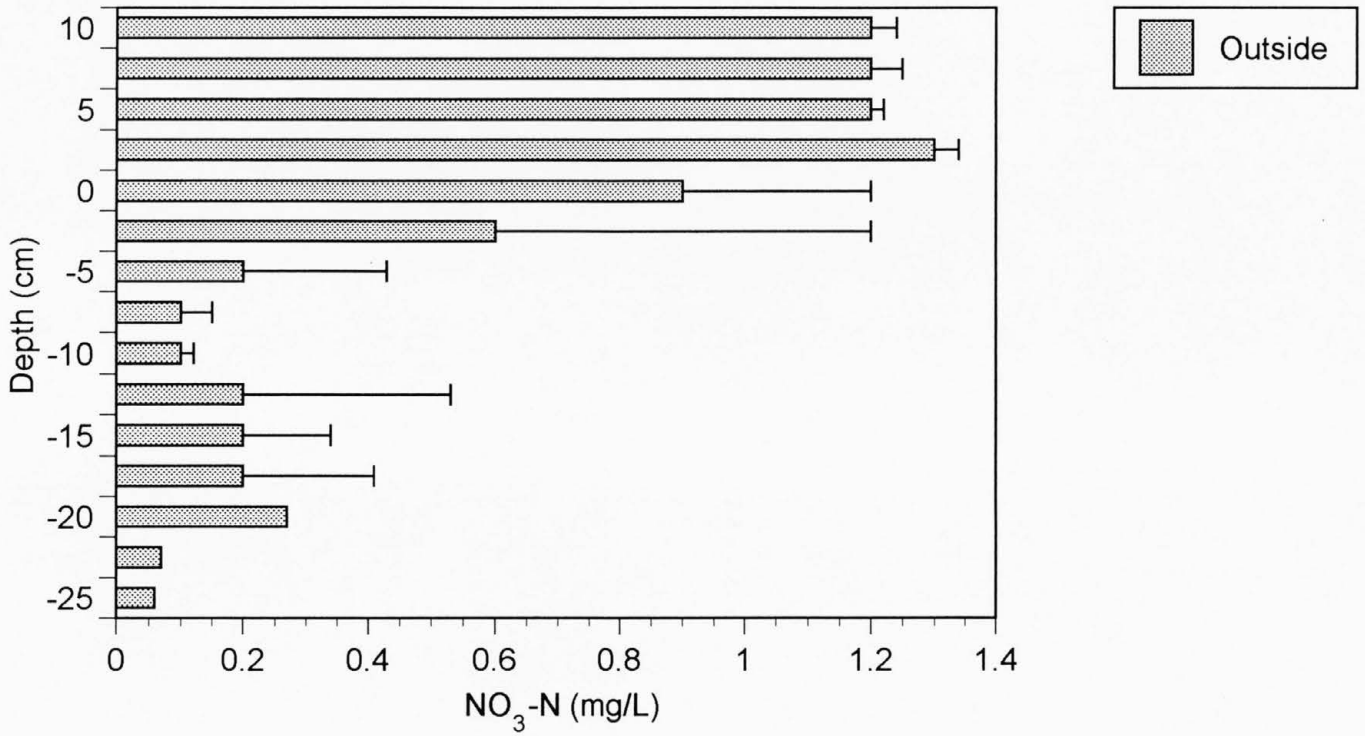

Figure 6. November nitrate concentrations outside the stand of Texas wildrice. Gray bars indicate mean concentrations of nitrate (mg/L) outside the stand at each depth. "0 cm" indicates the sediment-water interface. Error bars are +/- SD.

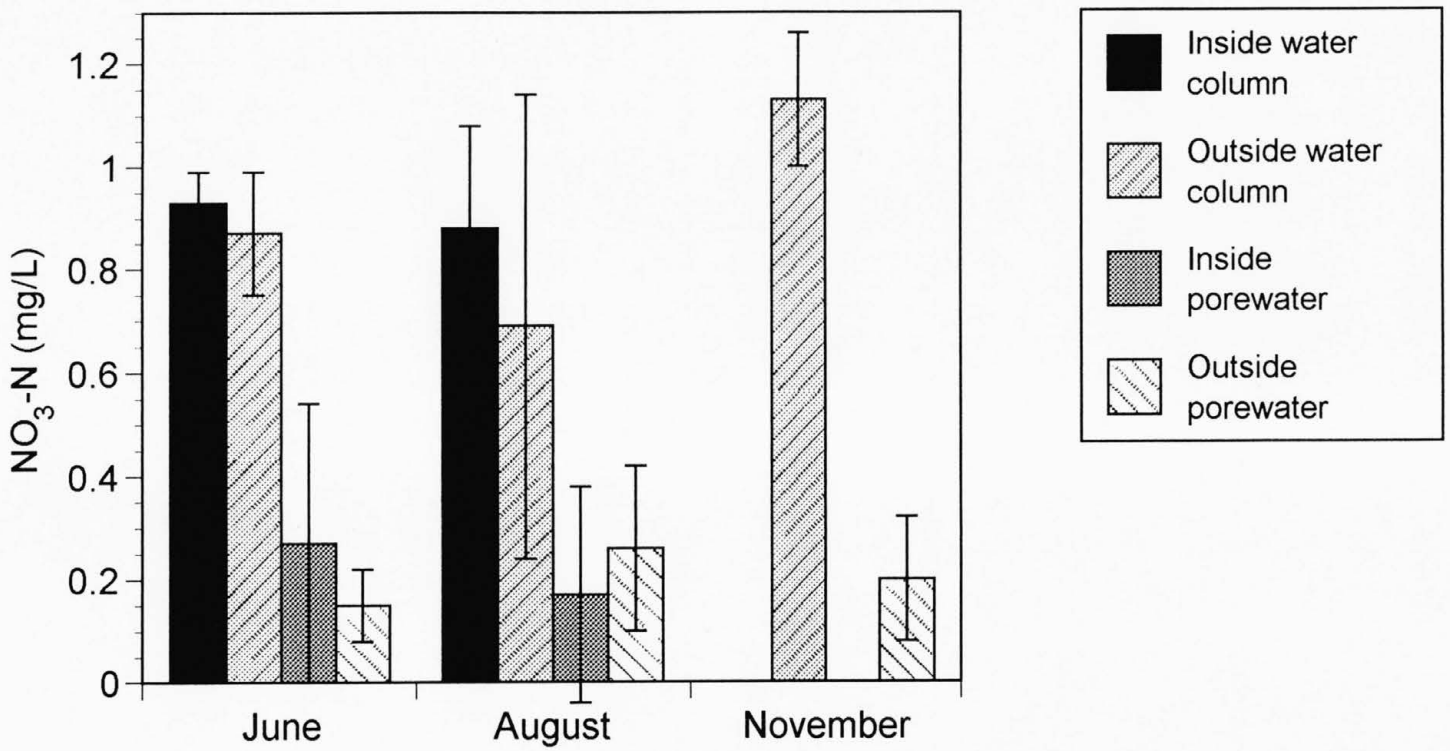

Figure 7. Mean nitrate concentrations for each month sampled. Solid bars represent the mean nitrate concentration inside the stand while open bars represent outside the stand. Error bars are +/- SD.

Phosphorus

Water column SRP concentrations were fairly consistent between months, though variability increased in the sediment profile (Figures 9 and 10).

In August, water column concentrations inside and outside the stand did not exceed 20 $\mu g\ L^{-1}$ and averaged 12 $\mu g\ L^{-1}$. Porewater SRP was highly patchy and exhibited a high amount of variation at each depth. In the sediment profile, concentrations increased slightly at about 5 cm into the sediments and reached a maximum concentration of 80 $\mu g\ L^{-1}$ at 15 cm (Figure 8). There were no influences on porewater SRP concentrations from either depth through the sediment profile or location (inside/outside).Mean SRP concentrations were significantly different between the water column and porewater ($p=0.002$) in August (Figure 10).

In November, SRP was around 13 $\mu g\ L^{-1}$ in the water column as well as the porewater (Figure 9). No significant differences were observed in depth through the sediment profile or between the water column and porewater (Figures 9 and 10).

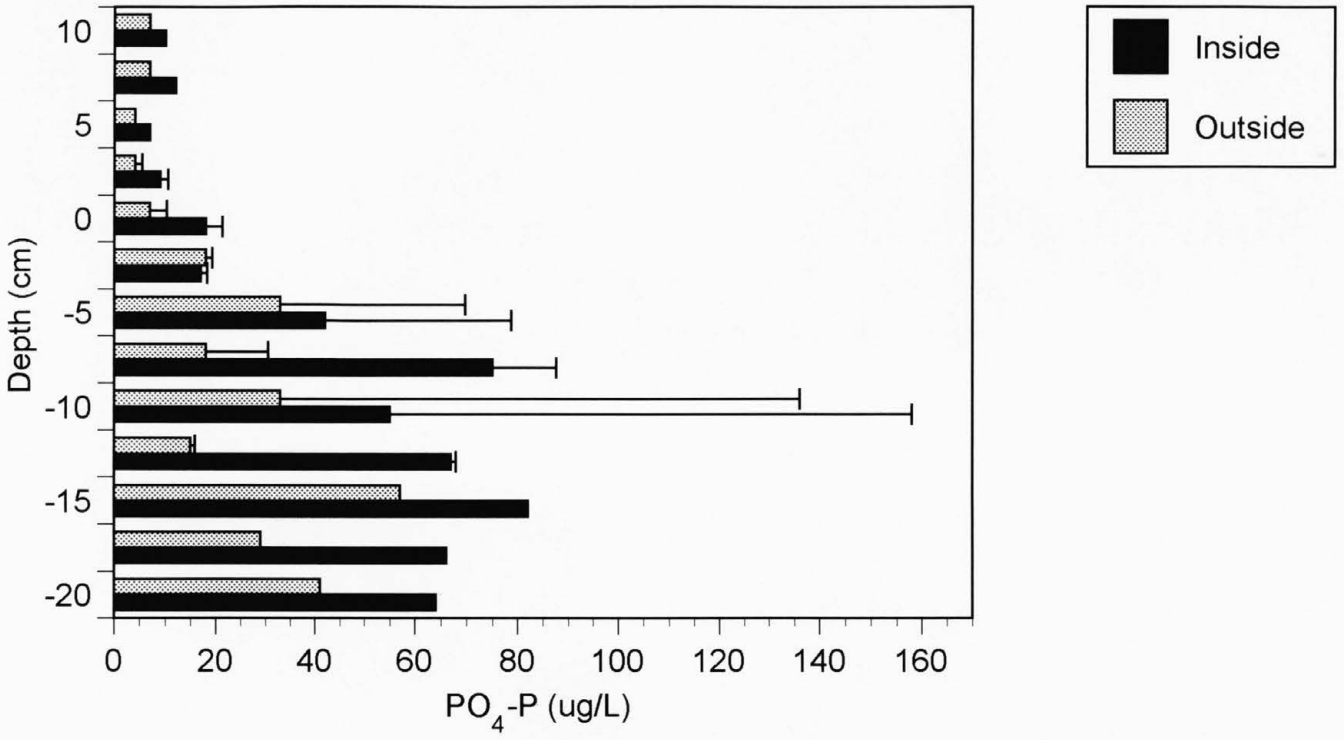

Figure 9. August soluble reactive phosphorus concentrations inside and outside the stand of Texas wildrice. Black bars indicate mean concentrations of SRP (ug/L) inside the stand at each depth while gray bars indicate concentrations outside. "0 cm" indicates the sediment-water interface. Error bars are +/- SD.

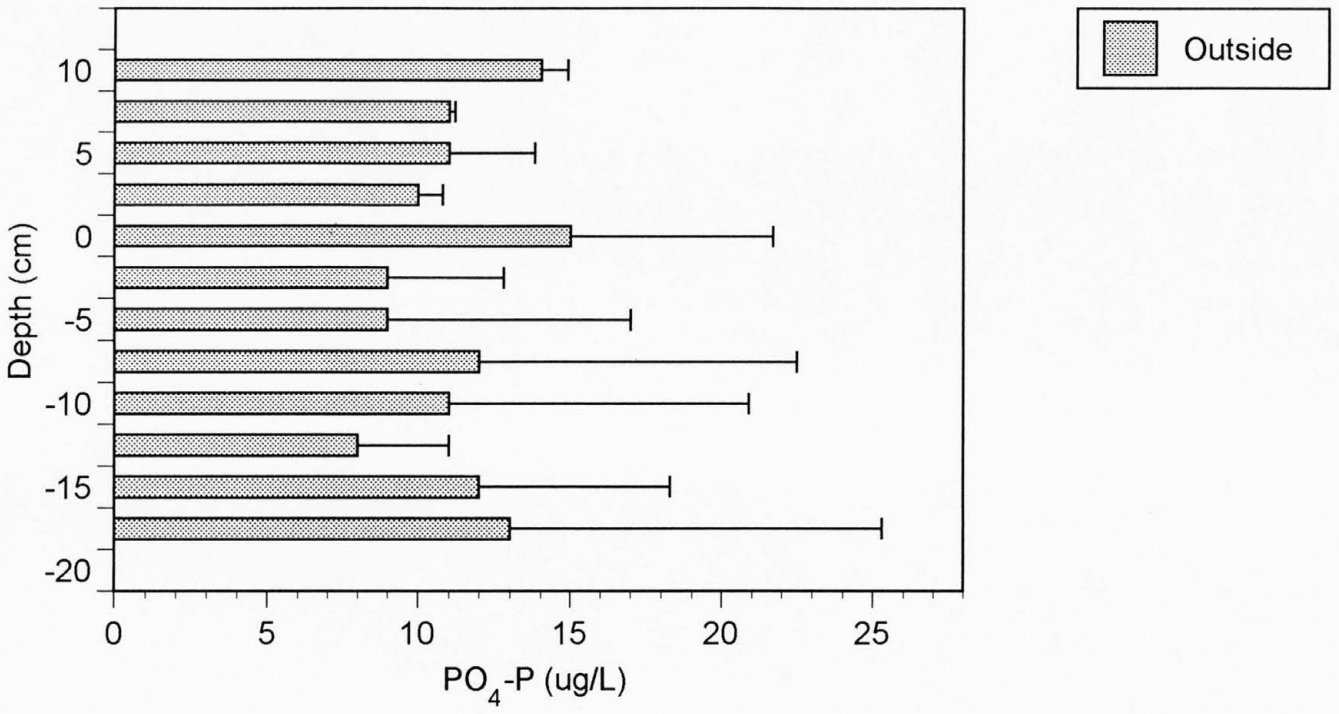

Figure 10. November soluble reactive phosphorus concentrations outside the stand of Texas wildrice. Gray bars indicate mean concentrations of SRP (ug/L) outside the stand at each depth. The sediment-water interface is indicated by "0" depth. Error bars indicate +/- SD.

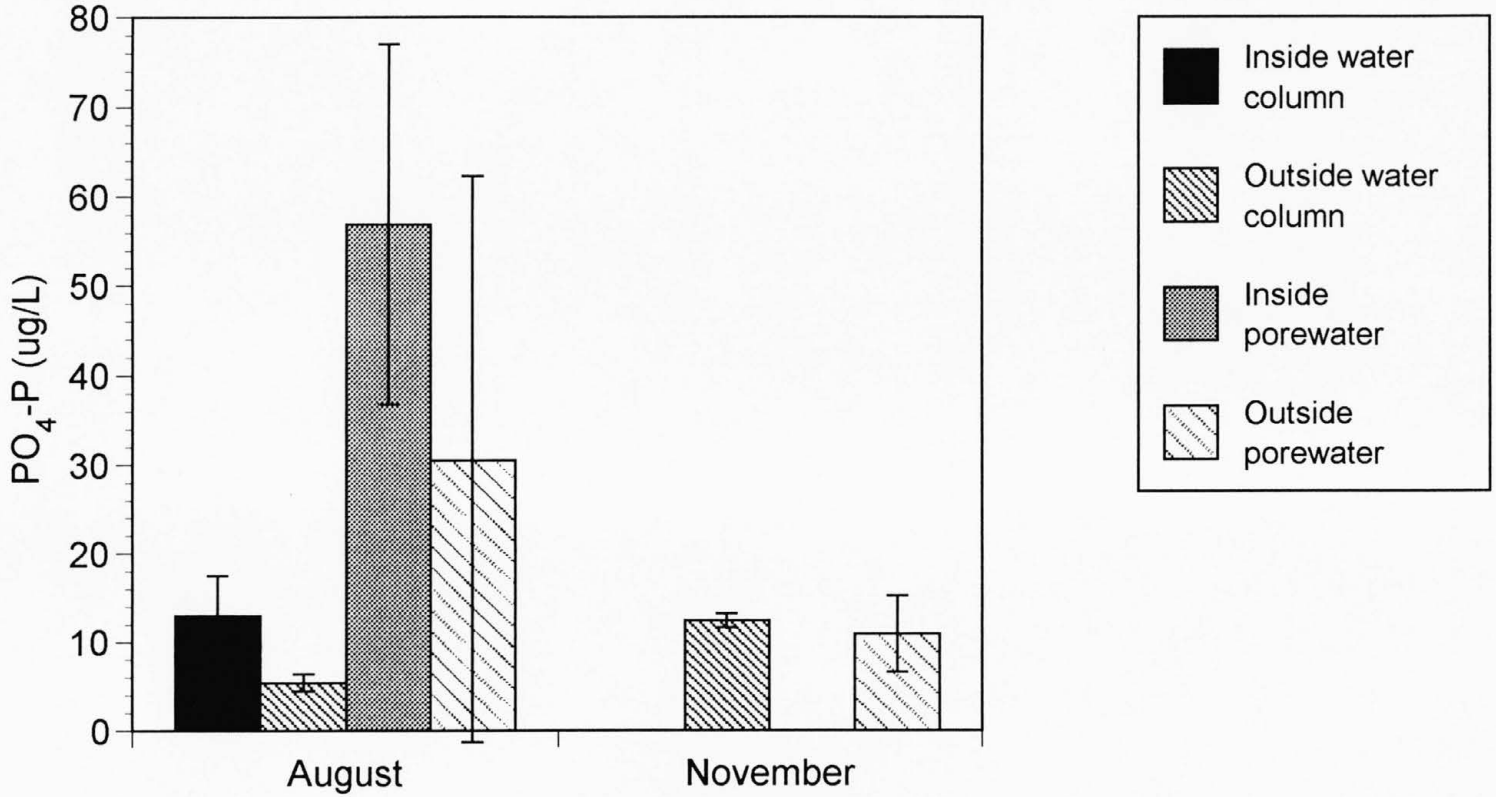

Figure 11. Mean soluble reactive phosphorus concentrations for August and November. Solid bars represent the mean nitrate concentration inside the stand while open bars represent outside the stand. Error bars are +/- SD.

Ammonium

Mean ammonium concentrations were higher in the porewater than the water column inside and outside the stand (Table 1). Water column concentrations were less than 0.10 mg L^{-1} NH_4-N in June and August inside and outside the stand. Mean porewater concentrations were over 0.8 mg L^{-1} in June inside the stand and August outside the stand. June porewater NH_4 inside the stand was significantly higher than outside the stand ($p=0.01$). The opposite trend was observed between inside and outside in August, however the difference was not significant.

Ammonium concentrations were not obtained in November due to the limited amount of water obtained from individual peeper chambers due to loss of membrane integrity upon insertion and/or removal of the peepers.

Table 1. Ammonium (mg/L NH_4-N) concentrations for June and August inside and outside the stand in the water column and porewater ±SD (*n*).

	Water Column (NH_4-N)	Porewater (NH_4-N)
June inside	0.06±0.02 (3)	0.85±0.57 (8)
June outside	0.02±0.02 (3)	0.26±0.28 (6)
August inside	0.07±0.02 (5)	0.51±0.35 (6)
August outside	0.10±0.05 (5)	0.81±1.27 (7)

Sediment analysis

Mean percent organic matter was significantly greater ($p=0.01$) inside the stand in August (8.26%) than outside (4.64%) (Figure 11). Organic matter outside the stand in August was only slightly higher than November.

Gravel content (>2.0 mm) was 30.8% of the dry weight inside the stand in August, 77.7% outside the stand in August, and 58.9% in November (Table 2). Soil content (<2.0 mm) was 69.2% inside the stand in August, 22.3% outside the stand in August, and 41.0% in November.

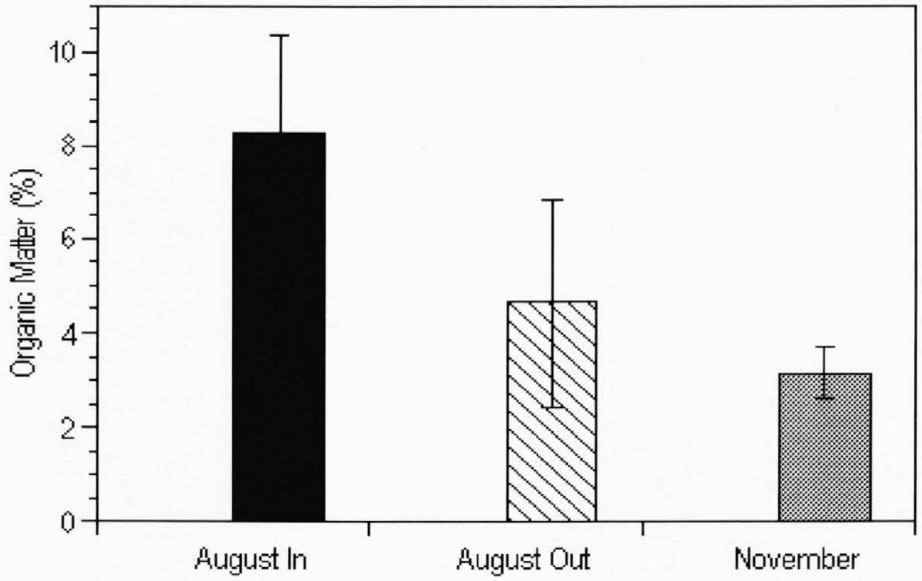

Figure 11. Percent organic matter inside and outside the Texas wildrice stand in August and outside the stand in November. Error bars are ±1 SD.

Table 2. Percent gravel and soil ±SD (n) in August inside and outside the stand of wildrice and November outside the stand.

	Gravel (%)	Soil (%)
August inside	30.8±15.22 (2)	69.2±15.22 (2)
August outside	77.7±1.05 (2)	22.3±1.05 (2)
November	58.9±19.5 (3)	41.1±17.6 (3)

Tissue nutrients

Mean ammonia concentrations were 29.4 mg g^{-1} dry weight NH_3-N in emergent leaves, 22.2 mg g^{-1} in submersed leaves and 37.5 mg g^{-1} in newly germinated shoots (Table 3). Mean ortho-P concentrations were 2.0, 1.7 and

3.25 mg g^{-1} dry weight for the emergent leaf blades, submersed leaf blades, and shoots, respectively.

Table 3. Tissue ammonia (NH_3-N) and ortho-phosphorus (P) (mg/g dry weight; mean ± SD (*n*)) of three growth forms of Texas wildrice; emergent, submersed and newly germinated shoot.

Leaf type	NH_3-N	P
Emergent	29.4 ± 0.63 (4)	2.0 ± 0.07 (4)
Submersed	22.2 ± 1.97 (3)	1.7 ± 0.26 (3)
Shoot	37.5 (1)	3.25 (1)

Nutrient limitation experiment

Growth of Texas wildrice in the nutrient limitation experiment was measured as dry mass of plant tissue, leaf length, and root:shoot ratio (r:s). There was a slight increase in plant mass between the control, low P, and high P treatments (ANOVA, $p<0.10$) and only a weak relationship existed between total plant mass and the P enrichment concentrations ($r=0.44$) (Figure 12). Dry plant mass was only slightly higher in the N+P treatment compared to the Low P treatment (t-test, $p=0.08$), indicating some enhanced growth by the addition of N.

The greatest increase in leaf length was observed in the N+P treatment (Figure 13). The least response was observed in the Low P treatment, which did not appear to respond until near the end of the experiment and did not differ from the responses observed in the control.

The highest r:s was observed in the Low P enrichment while the lowest ratio was in the P+N treatment; however, there were no significant differences between r:s ratios (ANOVA) (Table 4).

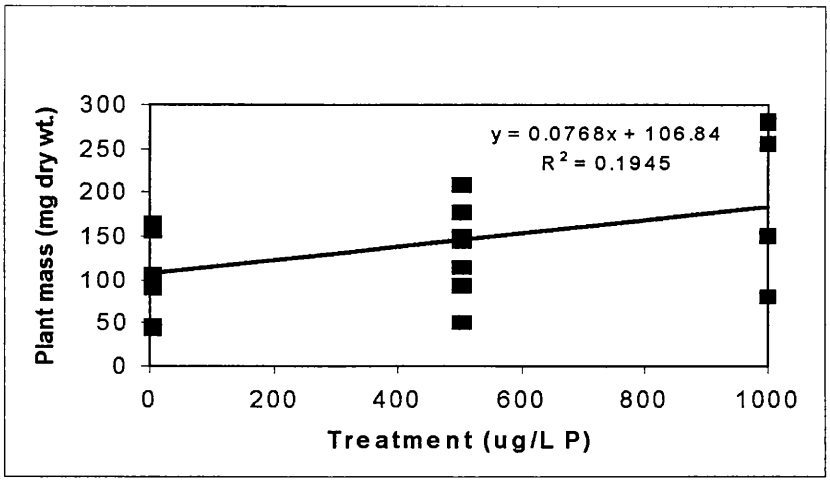

Figure 12. Plant mass (mg dry wt.) in the phosphorus enriched plants following the nutrient limitation experiment on Texas wildrice. "0" treatment indicates the control (unamended sand).

Table 4. Mean dry weights of Texas wildrice (mg) and the root:shoot ratios ±SD (*n*) following the nutrient limitation experiment .

Treatment	Plant mass (mg dry wt.)	Roots (mg)	Shoots (mg)	R:S
Control	114.12±49.1 (5)	23.1	91.1	0.25±0.11 (5)
Low P	134.81±53.4 (7)	27.1	107.7	0.29±0.12 (7)
High P	192.71±93.94 (4)	35.7	157.0	0.24±0.03 (4)
P + N	216.15±115.9 (6)	36.4	179.8	0.20±0.03 (6)

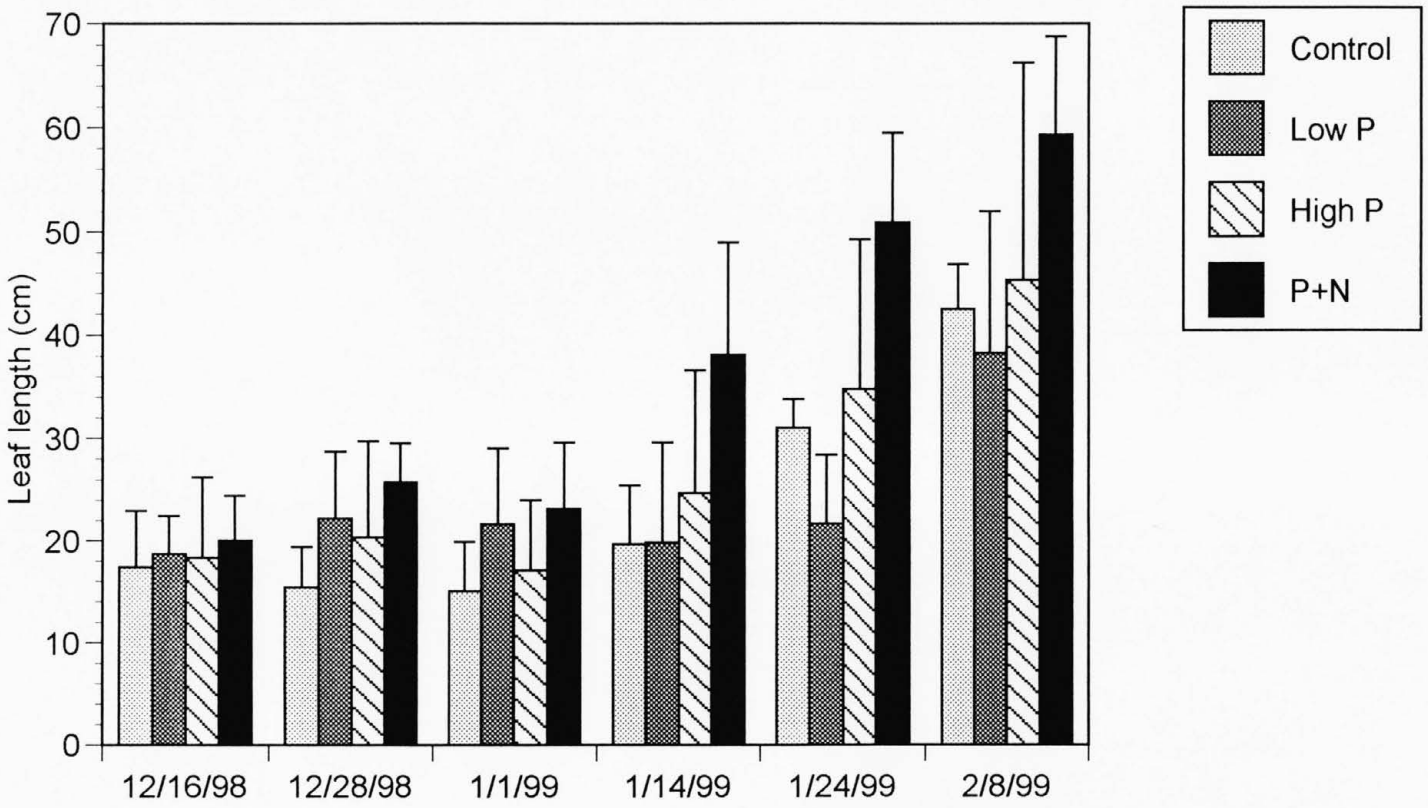

Figure 13. Mean leaf lengths (cm) during the nutrient limitation experiment. Nutrient additions were low P (500 ug/L), high P (1000 ug/L), N+P (1.5 mg/L N + 500 ug/L P) and unamended. Error bars are +/- SD.

DISCUSSION

Interstitial nutrients

Nitrate

Although trends in the sediment nutrient profiles were similar between months and between inside and outside the stand, actual concentrations were highly variable. Such variability could have been due to such factors as irregular diffusion gradients in the patchy sediment structure, and redox seasonal changes caused by variation in respiration and release of oxygen through plant roots.

In all months sampled, NO_3 concentrations significantly decreased with increasing depth in the sediment profile. Despite such decreases, NO_3 was still present as low as 25 cm into the sediments, possibly due to the redistribution of loose sediments and oxygen by river turbulence.

Higher NO_3 concentrations through the sediment profile inside the stand in June may have been a direct result of roots oxidizing adjacent sediments (Sand-Jensen and Prahl 1982). Chen and Barko (1988) demonstrated a redox potential as high as +300 mV at 3 cm into sediments planted with *Sagittaria*

latifolia, whose growth habit is similar to Texas wildrice. In their experiment, however, they ultimately concluded it was likely plant uptake of nutrients, and not redox conditions effecting the concentrations of N and P.

Lower sediment nitrate concentrations in August could have been a result of plant uptake during the growing season or microbial activity. Additionally, because NO_3 is more mobile than NH_4 it is more likely to be lost to nitrate reduction before it is absorbed (Mitsch and Gosselink 1993).

Though not statistically significant, the slight increase in water column nitrates in November could have been a result of flood waters from upstream tributaries. During the 17 October flood, a large amount of vegetation was uprooted from Spring Lake and the adjacent slough, causing thick brown plumes of water rich in particulates. Even a month after the flood, the San Marcos River remained turbid from Sink Creek, a tributary to the slough adjacent to Spring Lake.

Phosphorus

Water column SRP concentrations are consistent with previous research on the San Marcos River (Groeger et al.1997); however, SRP in the sediment profile is more difficult to quantify. There was an increase of SRP in the sediments in August, particularly inside the stand (Figure 8). Additionally, organic matter was nearly twice as high inside the stand as outside. Barko and Smart (1986) found increasing organic matter and P to be positively correlated in several lake sediments.

Jaynes and Carpenter (1986) found that increased redox potential caused sediments to retain nutrients as P and Fe. Perhaps sediments outside the stand in August are slightly lower in SRP because of increased oxygen and subsequent binding of P with calcium carbonate and ferric hydroxide (Chen and Barko 1988, Golterman 1998, Mitsch and Grosselink 1993, and Jaynes and Carpenter 1986).

SRP was very similar between the water column and porewater in November (Figure 10). Again, the 17 October flood deposited a layer of loosely compacted particles that may have allowed water to pass through the gravel substrate virtually unaffected (Table 2). The activity of the sediment biological community was also likely very low following the catastrophic flood.

When comparing November SRP to nitrate, it is interesting to note that nitrate was not similar between the water column and porewater as was the case with SRP (Figures 7 and 11). Perhaps N was more sensitive to changes in redox conditions in the sediments than P, causing the loss of NO_3 to either ammonium or nitrogen gas through denitrification (Chen and Barko 1988).

Laboratory studies have repeatedly indicated uptake of nutrients by aquatic macrophytes occurs primarily in the sediments (Barko and Smart 1980, Carignan and Kalff 1980, Barko et al. 1988, Chen and Barko 1988, Chambers et al. 1989). Nutrients are also replaced by deposition of decaying plant material or sediments being trapped in the plant stand (Barko and Smart 1980, Carpenter 1981).

All porewater nutrients exhibited patchiness in their concentrations. This

may be an accurate representation of sediment nutrients in the San Marcos River. The rapid current, continuous deposition and resuspension of sediments, patchiness of sediment composition, and diverse aquatic plant community may account for the lack of uniformity in nutrient distribution patterns. Additionally, shifts in the peepers during deployment may have caused individual peeper chambers to be misgrouped with respective chambers at the same level in the profiles. Though an attempt was made to insert peepers at uniform depths, they rarely remained at the same depth throughout the deployment period due to river currents and changes in the sediment texture through the profile. Even slight changes in depth can have profound effects on sediment redox (Chen and Barko 1988).

Ammonium

Water column ammonium was expectedly lower than sediment porewater. Generally, aquatic sediments are anoxic, favoring the formation and retention of NH_4-N over NO_3-N. The decrease in porewater NH_4-N from June to August inside the stand may have been caused by plant uptake, as NH_4-N is the preferred form of N for aquatic plants (summarized in Barko et al. 1991).

Sediment analysis

As expected, organic matter was higher inside the stand than outside in August (Figure 11). This was likely due to entrapment of particles under the leaf blades and decomposing leaves. Where organic matter was highest, inside the

stand in August, SRP was also higher; however, there was not a similar relationship between organic matter and nitrates. River sediment structure and resulting hydrologic environment (water velocity), appears to be a shifting mosaic within the upper San Marcos River over spatial and temporal scales.

Heavy sediment deposition was noted in Sewell Park, on the SWT campus, as a result of flood debris from Sessoms Creek, a tributary to the San Marcos River. Patches of Texas wildrice in the park were highly impacted after the flood. At least a 0.25 m of gravel was deposited on one stand in the park (personal observation).

At the study site, sediment deposition was so heavy that the stand and surrounding vegetation was nearly completely buried. This deposition explains the decreased organic matter content in November compared to August (Table 2) as well as the near equal distribution of soil and gravel (Table 2).

Nutrient Limitation Experiment

Nitrogen is frequently the limiting nutrient to aquatic macrophytes due to the limited amount in relation to phosphorus within the sediments (Barko et al. 1991). Best et al. (1996) found N to be the primary nutrient limiting the growth of *Elodea nuttallii.* Conversely, Carr and Chambers (1998) found P to be the primary nutrient limiting the growth of *Potamogeton pectinatus*. However, only 28% of the variability in macrophyte biomass was explained by sediment nutrients in that experiment. Carr and Chambers (1998) list an array of factors

that may also explain plant abundance in flowing waters, including sediment oxygen content and organic matter, herbivory, current velocity within plant stands, light availability, and interspecific competition.

The low r:s ratio in the N+P treatment is indicative of a N+P limitation or N limitation. Plants with a low r:s ratio are associated with more fertile substrates. There is more root growth in high ratio plants and more shoot growth in low ratio plants. The r:s ratio found in the N+P treatment is similar to ratios found by Power (1996b) when Texas wildrice was grown on sandy clay loam, which had the highest concentration of N of the sediment types tested.

There was a weak difference between P treatments (control, low P and high P) ($p<0.10$) and between N+P and low P treatments ($p<0.10$). This may have been influenced by loss of plants (and thus loss of *n*) from crayfish predation. Additionally, accumulation of epiphytes and cyanobacteria on the leaf blades appeared to inhibit photosynthesis throughout the experiment, creating several outliers in the N+P data. Without such outliers present, statistical significance increased greatly ($p<0.01$), contributing to the hypothesis that N is the limiting nutrient to Texas wildrice under these conditions.

CONCLUSIONS AND RECOMMENDATIONS

Texas wildrice does appear to influence sediment nutrients in its immediate surroundings, at least downstream under its leaf blades. Many studies conducted on aquatic macrophytes are on lakes, ponds, and mesocosms. With few exceptions (Chambers et al. 1989, Robach et al. 1995), there has been little published work conducted on the relationships between nutrients and macrophytes in flowing waters. This may be partly due to an increased urgency to manage lentic habitats where macrophytes are more problematic.

While it is unlikely that the population and distribution of Texas wildrice is solely determined by the nutrients in the sediments, it is likely that they change sediment nutrients once they are established. Although Texas wildrice is commonly found in a narrow band of flow regimes (0.29 to 0.63m s^{-1}) in the San Marcos River (Power 1996a, Poole and Bowles, in press), a small conservation population flourishes outside this regime.

Though the use of peepers in the San Marcos River was informative, I would not highly recommend them for future work under similar conditions. Given the nature of the sediments in the river and the fragility of the membranes in the peepers, they might be better served in the lakes and mesocosms they

were designed to sample. Either upon deployment or removal of the peepers, membranes were frequently torn by gravel, shells, glass, rocks, etc. in the sediments. Due to finer sediment size inside the stand, deployment and retrieval was much more efficient than outside the stand and the recovery of individual collection chambers in the peepers was much greater. Peepers should not be used in deep water or areas with high velocity.

Future examinations of the primary nutrients limiting the growth of Texas wildrice should use sediments from the San Marcos River and attention should be given to P+$CaCo_3$ and P+Fe interactions. Although sediment iron concentrations were not quantified, iron stains were commonly found on the peepers following deployment.

It would also be enlightening to investigate the nutrients inside the stand in relation to the root systems. That is, where is absorption by roots taking place and at what depth does it cease? In the conservation population of Texas wildrice on the SWT campus, adventitious roots frequently grow from their respective pots and into the water column or a neighboring pot. In very fast currents, Texas wildrice roots can be seen as large masses exposed to the upstream current, apparently pulled from the sediments or the sediments were washed away (as seen in Sewell Park).

The Texas wildrice stand examined in this research is currently emerging from the debris it was buried after the October flood. A post-flood nutrient examination would be interesting. A unique opportunity to observe the effects of flood on the sediment nutrients associated with Texas wildrice has presented

itself.

APPENDIX

Nutrient Limitation experiment began12/16/98 ended 2/8/99. Leaf lengths (cm) for the unamended (control), low P, high P and P+N treatments.

	Control	Low P	High P	P+N
12/16/98				
1	16.5	16.6	11.5	19
2	14.5	15	30.2	26.5
3		17	22	14.4
4	18.5	20.4	12	21
5	26	24.3	16	19.2
6	11.5			
Mean	17.4	18.7	18.3	20.0
SD	5.5	3.7	7.9	4.4
12/28/98				
1	16.2		10.4	21.4
2	13		29.2	28
3		17	21.3	
4	16.5	20		27.8
5	21	29.5		
6	10.5			
Mean	15.4	22.2	20.3	25.7
SD	4.0	6.5	9.4	3.8
1/1/99				
1	15.8		12.2	22.2
2	9			28
3		16	22	14.3
4	16	18.8		28
5	22	30		
6	12.2			
Mean	15.0	21.6	17.1	23.1
SD	4.9	7.4	6.9	6.5
	Control	Low P	High P	P+N
1/14/98				
1	15.5		15	44.5

Nutrient Limitation experiment began12/16/98 ended 2/8/99. Leaf lengths (cm) for the unamended (control), low P, high P and P+N treatments.

	Control	Low P	High P	P+N
2	12		38	45
3		10	21	22
4	25	20		41
5	25	29.5		
6	20.5			
Mean	19.6	19.8	24.7	38.1
SD	5.8	9.8	11.9	10.9
1/24/99				
1	29			55.5
2			45	55.5
3		16	24.5	38
4	29	20		54.5
5	31	29		
6	35			
Mean	31.0	21.7	34.8	50.9
SD	2.8	6.7	14.5	8.6
2/8/99				
1	36.5			61
2			60	59
3		22.5	30.5	47
4	45	45.5		70
5	46.5	47		
6	42			
Mean	42.5	38.3	45.3	59.3
SD	4.4	13.7	20.9	9.5

Peeper NO_3-N

June - inside	Peeper	15 cm	12.5	10	7.5	5	2.5	0	"-2.5	"-5	"-7.5	"-10	"-12.5	"-15	"-17.5	"-20	"-22.5	"-25
	A	"-	"-	0 96	0.94	0.96	1 06	0 99	0.97	0.91	0 74	0.03	0.03	0.03	0.02	"-	"-	"-
	B	"-	"-		1	0.95	0 93	1	0.04	0.04	0 05	0.05	0.05	*0.02*	0.05	0.16	"-	"-
	C	"-	"-		0.81	0.94	0 85	0.8	0.07	0.03	0.06	0.04	0.08	0.04	0 06	"-	"-	"-
	D	"-	"-		0.92	0.91	0.86	0.91	0.71	0.59	0.76	0 88	0 82	0.8	0.08	0.17	"-	"-
	Mean			**0.96**	**0.92**	**0.94**	**0.93**	**0.93**	**0.45**	**0.39**	**0.40**	**0.25**	**0.25**	**0.22**	**0.05**	**0.17**		
	SD				**0.08**	**0.02**	**0.10**	**0.09**	**0.47**	**0.43**	**0.40**	**0.42**	**0.38**	**0.39**	**0.03**	**0.01**		
June - outside	A	"-	"-	0.98	1.02	0.91	0.99	0.94	0.13	0.49	"-	"-	"-	0 07	0.06	"-	"-	"-
	B	"-	"-	0 92	0 92	1 03	1.11	0.94	*0.86*	0.21	0 07	0.05	"-	"-	"-	"-	"-	"-
	C	"-	"-	0.92	0.88	0.64	0.91	0.94	*0.86*	0.19	0.24	"-	0.28	0 24	"-	"-	"-	"-
	D	"-	"-	*0.97*	0.87	0.81	0.75	0.29	0.04	0.22	"-	"-	0.08	0.05	0.03	"-	"-	"-
	Mean			**0.95**	**0.92**	**0.85**	**0.94**	**0.78**	**0.47**	**0.28**	**0.16**	**0.05**	**0.18**	**0.12**	**0.05**			
	SD			**0.03**	**0.07**	**0.17**	**0.15**	**0.33**	**0.45**	**0.14**	**0.12**		**0.14**	**0.10**	**0.02**			
August - inside	A	0.84	0.79	1.01	1.05	0.99	1.03	1.01	0.92		0.44	0.05	*0.02*	"-	"-	"-	"-	"-
	B		"-	"-	0.99	1.01	1.03	0 95	*0.02*	0.01	0.04	0.05	0.02	0.04	0.06	"-	"-	"-
	C		"-	"-	"-		0.94	1 04	*0.02*	0.03	0.03	0.02	0.22	0.22	0.21	0.05	"-	0 15
	D		"-	"-	"-	0.78	0.9	0.05	0.04	0.05	0.04	0.05	0.11	0 05	0.06	*0.02*	0.04	"-
	Mean	**0.84**	**0.79**	**1.01**	**1.02**	**0.93**	**0.98**	**0.76**	**0.25**	**0.03**	**0.14**	**0.04**	**0.09**	**0.10**	**0.11**	**0.04**	**0.04**	**0.15**
	SD				**0.04**	**0.13**	**0.07**	**0.48**	**0.45**	**0.02**	**0.20**	**0.02**	**0.10**	**0.10**	**0.09**	**0.02**		
August - outside	A	"-	"-	0.84	0.85	0 71	0 78	0 74	0.12	0.04	0.04	0.04	"-	0.06	"-	"-	"-	"-
	B	"-	"-	"-	"-	"-	"-	"-	0.46	0.63	0.09	0 11	"-	"-	"-	"-	"-	"-
	D	"-	"-	1 04	1.18	1.15	0 95	1.14	1.13	1 04	0.2	0.11	0.07	0.05	"-	"-	"-	"-
	Mean			**0.94**	**1.02**	**0.93**	**0.87**	**0.94**	**0.57**	**0.57**	**0.11**	**0.09**	**0.07**	**0.06**				
	SD			**0.14**	**0.23**	**0.31**	**0.12**	**0.28**	**0.51**	**0.50**	**0.08**	**0.04**		**0.01**				
November	A	"-	"-	"-	"-	"-		1 32	0.57	0.08	0.05	0.13	0.1	0 72	0.34	0 49	0.27	0.07	0.06
	B	"-	"-	1.26	1.18	1.26	1.26	1 3	1.2	0.52	0.08	0.09	0.06	0.24	0.06	"-	"-	"-
	C	"-	"-	1 26	1.27	1.22	1.26	0.7	0.05	0.02	0.03	0 07	0.05	0.04	0 05	"-	"-	"-
	D	"-	"-	1.19	1.26	1.24	1.22	1.00	1.00	0.15	*0.02*	0.11	0 05	0.08	0.08	"-	"-	"-
	Mean			**1.24**	**1.24**	**1.24**	**1.27**	**0.89**	**0.58**	**0.19**	**0.07**	**0.09**	**0.22**	**0.18**	**0.17**	**0.27**	**0.07**	**0.06**
	SD			**0.04**	**0.05**	**0.02**	**0.04**	**0.33**	**0.60**	**0.23**	**0.05**	**0.02**	**0.33**	**0.14**	**0.21**			

Peeper SRP																				
August - inside	**A**	"-	"-	10.4	6 6	8.3	8.5	10.5	"-	"-	"-	37.7	108.9	"-	"-	"-	"-	"-		
	B	"-	"-	"-	17.7	"-	13 2	18.2	"-	40.6	62.1	"-	15.4	"-	25.8	"-	"-	-		
	C	"-	"-	"-	"-	"-	8	26.7	12.2	47.3	99.2	66.7	119.1	132.2	105.5	"-	"-	16.5		
	D	"-	"-	"-	"-	6	5.2	16.3	22.04	37	63 4	60.2	25.8	31 7	"-	63.6	"-	"-		
	Mean			**10**	**12**	**7**	**9**	**18**	**17**	**42**	**75**	**55**	**67**	**82**	**66**	**64**		**17**		
	SD				**7.85**	**1.63**	**3.32**	**6.70**	**6.96**	**5.23**	**21.05**	**15.22**	**54.25**	**71.06**	**56.36**					
August - outside	**A**	"-	"-	"-	"-	"-	"-	-		22 1	72.5	26.83	151.1	"-	"-	116	"-	"-	"-	
	B	"-	"-	"-	"-	"-	5.4	5	-	-	4.3	5.4	16.8	"-	"-	"-	"-	"-		
	D	"-	"-	7.4	5.7	6.2	3.3	9.6	23.9	20.7	5.9	-	15.5	11.7	"-	"-	"-	"-		
	Mean			**7**	**7**	**4**	**4**	**7**	**18**	**33**	**15**	**57**	**29**	**41**						
	SD						**1.48**	**3.25**	**1.27**	**36.63**	**12.57**	**103.03**	**0.92**							
November	**A**	"-	"-	"-	"-	"-	9.4	15.7	11.7	19.9	27.2	7	"-	"-	"-	"-	"-	"-		
	B	-	-	14.9	11.2	11.1	10.3	11.5	12	8.9	7.5	22.1	10.6	-	-	-	-	-		
	C	-	-	13.8	11.4	14.4	11.4	8.4	4.1	3.1	8.4		9	16.2	4.6	-	-	-		
	D	-	-	13	11.6	8.8	10 5	23 9	7.3	2.8	3.8	3.5	4.8	7.3	22	-	-	-		
	Mean			**14**	**11**	**11**	**10**	**15**	**9**	**9**	**12**	**11**	**8**	**12**	**13**					
	SD			**0.95**	**0.20**	**2.81**	**0.82**	**6.72**	**3.79**	**7.99**	**10.51**	**9.88**	**3.00**	**6.29**	**12.30**					

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