Plant Nutrient Uptake and Biomass Accumulation in a Constructed Wetland

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ABSTRACT

We examined the role of plants in the nutrient cycle of a 0.3 ha constructed wetland that received tile drainage water from agricultural fields. The objectives were to determine: 1) above- and below-ground production of wetland macrophytes; 2) production of algae; 3) accumulation and uptake rate of N and P by vegetation during the growing season; and, 4) role of wetland vegetation in the overall N and P budgets. Total biomass ranged seasonally from 12000 to 30000 kg ha^{-1} in the wetland, reaching a maximum in September, with roots accounting for 54 to 77% of the total. Above-ground macrophyte biomass ranged from 2000 to 5700 kg ha^{-1}, and also reached a maximum in September. Algae were only present early in the growing season and had a maximum biomass of 233 kg ha^{-1} at the end of May. During the 1998 water year, tile input transported 715 kg ha^{-1} total N and 10 kg ha^{-1} total P into the wetland, whereas wetland output was 256 kg total N ha^{-1} (256 kg ha^{-1} in outlet flow and 120 kg ha^{-1} in seepage) and 7.3 kg total P ha^{-1}. Therefore, the wetland removal efficiencies for N and P were 47 and 29%, respectively. Total N and P in biomass reached maxima of 367 and 57 kg ha^{-1} respectively, with below-ground biomass accounting for most of the N and P found in plants. Although the N accumulation by wetland plants was equal to the difference between the wetland input and output for N, most of the plant growth occurred after tile flow ceased. Plant removal of N and P from the water column was likely a small component of the overall effectiveness of the wetland due to the lack of synchronization between plant growth and tile flow.

INTRODUCTION

In Illinois much of the land is under high intensity row-crop agriculture where soils are heavily fertilized. About 35% of Illinois cropland (~4,000,000 ha) is drained by perforated subterranean tile lines (USDA 1987), which drain into surface waters and often flow into drinking water reservoirs. Tile drainage from agricultural fields can cause concentrations of NO_3^- in surface waters of Illinois to exceed health

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advisory standards of 10 mg N L^{-1} (David et al. 1997a). Designing wetlands that intercept tile drainage may be one possible method of decreasing the amount of NO_3^- entering surface waters.

Kovacic et al. (2000) examined the removal of NO_3^- from three constructed wetlands receiving agricultural tile drainage. These wetlands removed about 36% of the N from tile drainage water, and when the effects of riparian buffer strips were added, N removal was as high as 45% of inputs (Kovacic et al. 2000, Larson et al. 2000). In the same wetlands, Xue et al. (1999) showed that the predominant removal mechanism of NO_3^- from the water column was by denitrification. Finally, David et al. (1997b) determined that NO_3^- removal rates in the spring were higher in wetland mesocosms containing plants than without plants, and also found that during the summer removal rates were enhanced with the addition of sucrose. Collectively, these studies quantified wetland nutrient inputs and outputs, identified the primary NO_3^- removal mechanism, and investigated the influence of available C on NO_3^- removal rates; however, the direct impact of plants on nutrient cycling was not studied.

Plants are an integral part of wetland processes. Freshwater macrophytes can affect wetland function by: 1) assimilating nutrients from sediments and incoming water; 2) affecting the rates of denitrification; and 3) altering wetland processes on a temporal basis by acting as a source/sink during certain seasons (Sloey et al. 1978). Numerous studies have documented the ability of freshwater macrophytes to mobilize and accumulate nutrients, especially N and P (Gerloff and Krombholz 1966, Toetz 1974, Welch and Denny 1979, Barko and Smart 1981, Caffrey and Kemp 1992, McJanet et al. 1995). In addition, several studies have investigated the role of plants as a carbon source for denitrifying bacteria (Carpenter and Lodge 1986, McCarty and Bremner 1993, Saarinen 1996). Recent studies have also shown that metaphyton biomass can be high in newly constructed wetlands (135-335 g dry mass m^{-2}) and can account for much of the P retention in these systems (Wu and Mitsch 1998). These authors also indicated metaphyton biomass was greatest near the inlets of constructed wetlands (where nutrients levels were highest) and declined toward the outlet. Gurney and Robinson (1987) demonstrated a significant negative correlation between metaphyton cover and the density of emergent vegetation, suggesting algal mats increase shading of emergent vegetation, which decrease their growth. Overall, these wetland studies show strong supporting evidence for both direct and indirect effects of plants in nutrient removal, especially for N; however, the temporal relationship among wetland hydrology, plant biomass, and nutrient accumulation has not been well documented, particularly for wetlands receiving agricultural runoff.

This study was conducted to examine the role of plants in the cycling and removal of NO_3^- and P from a wetland receiving agricultural drainage water. Specific objectives were to determine the above- and below-ground production of wetland macrophytes; production of algae; the accumulation and uptake rate of N and P by vegetation during the growing season; and the role of wetland vegetation in the overall N and P budgets.

MATERIALS AND METHODS

Site Description

The study site was located along the Embarras River in Champaign Co. about 20 km south of Champaign-Urbana, Illinois. The study was conducted in wetland B,

one of four wetlands constructed in 1994 to intercept agricultural tile drainage lines. At full pool the wetland was approximately 37 m by 99 m, with an approximate surface area and volume of 0.30 ha and 1400 m^3, respectively. The wetland received tile drainage from 5.0 ha of agricultural land in a corn/soybean (*Zea maize* L./*Glycine max* L.) rotation where soybean was grown in 1998. Because vegetation and substrate were not disturbed during wetland construction, preexisting macrophytes comprised the initial wetland vegetation. Seeds were not introduced into the wetlands. Flood intolerant species were replaced by species within the preexisting seed bank of the wetlands and the adjacent floodplain. The most abundant macrophyte species (by biomass) in the wetland were reed canary grass (*Phalaris arundinacea* L.), sedge (*Carex* spp.), water smartweed (*Polygonum amphibium* L.), and smartweed (*Polygonum punctatum* Ell.). During 1998, filamentous green algae were present from mid-May until the wetland drew down in late-July.

Water Budget and Water Analysis of Wetland

Precipitation was measured on site with a Campbell Scientific TE525 tipping bucket rain gauge and rainfall data was recorded every 30 minutes with a Campbell Scientific CR10 datalogger (Gentry et al. 1998). The wetland inlet monitoring station was fitted with a combination weir plate (a slot and v-notch for estimating low and moderate flow rates and a crest for high rates) (Gentry et al. 1998). The outlet monitoring station contained a flash-board riser system which included an outlet orifice (3.81 cm^2) below a crest (Konyha et al. 1995). At both of the monitoring stations a datalogger, Keller PSI pressure transducer, and an ISCO Model 2900 automatic water sampler were installed (Gentry et al. 1998). At the inlet station, the datalogger recorded tile flow every 15 minutes. Water samples were collected on a volume increment based on tile flow characteristics that provided flow proportional sampling during a subsurface runoff event. As with the inlet, outlet flow was recorded every 15 minutes; however, samples were collected every six hours. Water samples and flow data were collected within 24 hours after peak flow events. Based on flow hydrographs of the inlet and outlet, water samples were selected for analysis to best represent the water quality of a given flow event by selecting samples during the rising limb, at maximum flow, and during the falling limb.

Inlet water samples were filtered (1.2 μm glass fiber) and analyzed for NO_3^--N by ion chromatography, NH_4^+-N by automated phenate method on a Technicon AutoAnalyzer, and dissolved reactive phosphorus by ascorbic acid colorimetric techniques (APHA 1995). The wetland outlet water samples were divided into filtered and unfiltered aliquots. The filtered aliquots were analyzed for NO_3^--N, NH_4^+-N and dissolved reactive P. The unfiltered aliquot was digested using persulfate for total N analysis followed then analyzed by cadmium reduction on a Technicon AutoAnalyzer (APHA 1995). The unfiltered aliquot was also used for total P analysis by digestion with sulfuric acid and ammonium persulfate and ascorbic acid colorimetric technique (APHA 1995). Organic N was determined by subtracting NO_3^--N and NH_4^+-N from total N. Organic P was determined by subtracting dissolved reactive P from total P. Total N and P were not measured in the tile inlet water because earlier NO_2^-, organic N, and organic P concentrations were found to be negligible and were discontinued (Kovacic et al. 2000).

Evapotranspiration (ET) estimates from the Illinois Climate Network data in Champaign, IL were combined with the surface area of the wetland to calculate

daily wetland water loss. Kovacic et al. (2000) estimated seepage at 50000 L d^{-1} using techniques described in Larson et al. (2000). Seepage water volume estimates were determined by multiplying the daily seepage rate by the number of days when the wetland contained a minimum volume of 50,000 L. Seasonal estimates of NO_3^- content in seepage water were made using values from Larson et al. (2000).

Soil Nutrients

In October 1997 five soil sampling sites were located along a transect parallel with the berm at five equidistant points across the middle of the wetland. Using a 1.9 cm diameter soil corer, three soil cores at each site were collected and divided into two depths (0 to 10 and 10 to 30 cm). The three core subsamples were bulked, air-dried, sieved (2 mm), and subsamples ground to 40 mesh (~0.4 mm). Oven-dry mass was determined at 105°C, and used to correct all measurements on air-dry soils. The sieved soil was used in the determination of extractable P using Bray 1 (Olsen and Sommers 1982). The ground soil was analyzed for total N using Kjeldahl digestion (Bremner and Mulvaney 1982) followed by a measurement of NH_4^+ using an automated phenate method (APHA 1995).

Macrophyte Biomass

Four 31 to 37 m long sampling transects were established perpendicular to the berm. The transects were spaced 20 m apart with five sampling sites randomly located along each transect (n = 20). Above- and below-ground biomass was sampled five times throughout the growing season from 28 May to 27 October 1998. Above-ground biomass was collected by clipping the vegetation at the soil surface at each sampling location using 0.25 m^2 quadrats. Each sample was separated into live and dead plant (litter) material, and live material was then separated by species. For below-ground biomass, three quadrats from each of the four transects were sampled (n = 12); however, due to the drying and hardening of the wetland soil after draw down, the sampling technique was modified. In the May-August sampling periods, two cores were taken from each quadrat using a 5.4 cm diameter PVC pipe to a depth of 25 cm. The two cores were combined and then washed and sieved to separate the root material. In September and October, six 1.59 cm diameter cores were taken from each quadrat to a depth of 25 cm. The six cores were combined then washed and sieved to separate the root material. All samples (above- and below-ground) were dried at 65°C for 48 hours and then weighed to determine dry mass. Above-ground biomass was separated by plant type, in categories of grasses (all grass species), sedges (all sedges and rushes), algae (all metaphytic algae), and others (forbs and woody plants).

Algal Biomass

Three sampling locations were randomly selected along each of the four transects (n = 12). At each sampling location, a 0.144 m^2 box sampler (an open ended metal box placed vertically in the water column) was used to collect algae samples. The samples were washed free of litter and sediment, dried at 65°C for 48 hours and then weighed to determine dry mass. Algal biomass was sampled twice during the 1998 growing season when the wetland contained water.

Nitrogen and Phosphorus Content of Vegetation

From each plant sample, a subsample was ground to pass a 20 mesh screen. Total N was determined by Kjeldahl digestion (Parkinson and Allen 1975),

converting all N to NH_4^+, with NH_4^+ measured using a Technicon AutoAnalyzer. Total P was determined using ammonium molybdate/ammonium metavandate (Jackson 1958) colorimetric technique on the digested samples used for N.

Mass and Flux Calculations

All mass and flux amounts have been put on a per ha basis, to facilitate comparisons with other studies. Because the wetland was 0.3 ha in size, to obtain the absolute mass or flux multiply by 0.3.

RESULTS AND DISCUSSION

Water Budget

Tile inlet flow for the wetland was continuous from the beginning of the water year through 16 August 1998, after which inflow stopped (Fig. 1). Although inlet tile flow occurred throughout much of the water year, large precipitation events dominated tile flow volumes. Tile inlet flow totaled 87600 m^3 ha^{-1} for the water year (Table 1), with the majority of flow (81%) during January through June. The research site received 1010 mm of precipitation during the 1998 water year, an average year of precipitation.

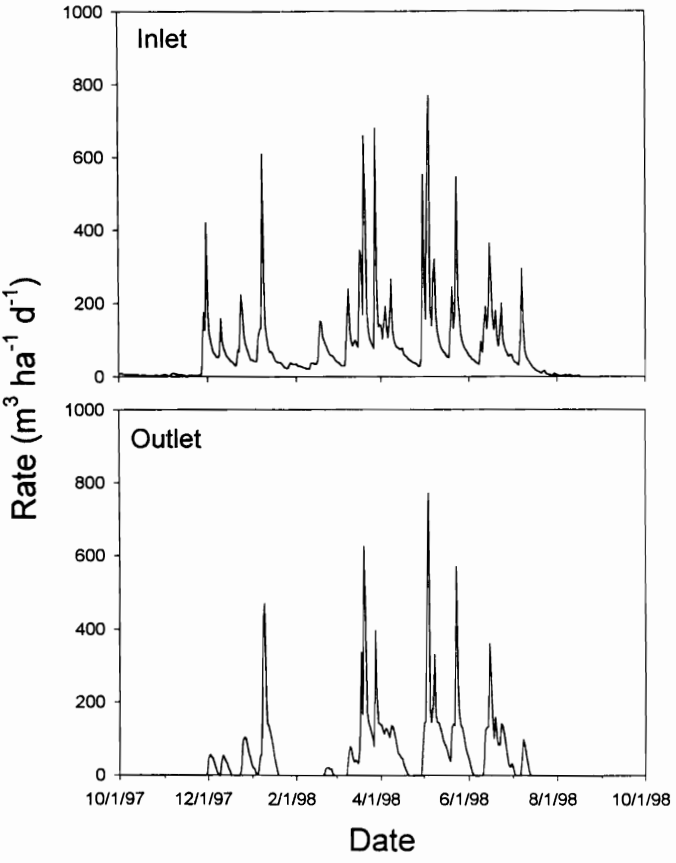

Figure 1. Daily water flow for the inlet and outlet of the wetland during the 1998 water year.

Wetland outlet flow occurred intermittently from 30 November 97 through 12 July 98. The total volume of outlet flow during the 1998 water year was 56900 m^3 ha^{-1} (Table 1). Outlet flow varied throughout the year, and was a function of inlet flow and wetland capacity. When high flow events occurred and wetland volume was at capacity, outlet flow volume equaled that of the inlet. Daily ET values ranged from 73 m^3 ha^{-1}, with total ET of 10300 m^3 ha^{-1} for the water year. The estimate of seepage exiting the wetland was 41000 m^3 ha^{-1} during the 1998 water year, which indicated that approximately 10700 m^3 ha^{-1} of water entered the wetland via surface runoff.

Nutrient Input/Output Budgets

The wetland received 715 kg N ha^{-1} from the tile inlet during the 1998 water year (Table 1). Almost all of this N (> 99%) was as NO_3^--N, with the remainder NH_4^+-N. Tile inlet flow had daily total N loads ranging from 0 to 18 kg N ha^{-1} d^{-1}. The wetland received approximately 6 kg N ha^{-1} in wet deposition and 4 kg N ha^{-1} in dry deposition during the water year (David et al. 1997a). Outlet flow contained about 256 kg N ha^{-1} during the water year, occurring as NO_3^--N (239 kg N ha^{-1}), NH_4^+-N (2.7 kg N ha^{-1}), and organic N (14 kg N ha^{-1}). Seepage loss of N was estimated at 120 kg N ha^{-1} in the form of NO_3^--N. The total output of N from both outlet flow and seepage was 377 kg N ha^{-1}, with an N removal rate for the wetland of 47% for the 1998 water year. This was similar to the average total N removal rate of 44% for this wetland during the previous three water years, where yearly N removal rates ranged from 36 to 48% (Kovacic et al. 2000).

Table 1. Monthly inlet and outlet flow and N forms for wetland B during the 1998 water year. Water year began 1 October and ended 30 September the following year.

	Inlet				Outlet				
Month	Flow	NO_3^--N	NH_4^+-N	Total N	Flow	NO_3^--N	NH_4^+-N	Organic N	Total N
	m^3 ha^{-1}	kg N ha^{-1}			m^3 ha^{-1}	kg N ha^{-1}			
Oct	6000	4	0.0	4	0	0	0.0	0.0	0
Nov	2900	19	0.0	19	10	0	0.0	0.0	0
Dec	8400	78	0.0	78	3500	11	0.2	0.7	12
Jan	8500	72	0.0	72	6700	26	0.4	2.1	28
Feb	5100	49	0.0	49	400	0	0.0	0.1	0
Mar	17100	136	0.5	136	12400	72	0.5	1.9	74
Apr	10400	92	0.2	92	5900	19	0.3	1.4	20
May	19200	149	0.2	149	18800	68	1.0	6.2	76
Jun	11000	85	0.3	85	8100	43	0.3	0.8	44
July	4100	28	0.0	28	1100	1	0.0	0.8	1
Aug	200	1	0.0	1	0	0	0.0	0.0	0
Sep	0	0	0.0	0	0	0	0.0	0.0	0
Sum	87600	713	1.2	715	56900	239	2.7	13.8	256

For P, inlet flow contained 10.2 kg P ha^{-1} in the form of dissolved reactive P (Table 2), with daily P loads ranging from 0 to 0.8 kg P $ha^{-1}d^{-1}$. Outlet flow contained 7.3 kg P ha^{-1} for the water year, in the form of dissolved reactive P (6.3 kg P ha^{-1}) and organic P (1.0 kg P ha^{-1}). The P removal rate was therefore 29% for the 1998 water year. Kovacic et al. (2000) found that P removal rates were highly variable during the preceding three year period with rates ranging from minus (-) 13 to 80%, indicating that this wetland can act as either a net source or sink.

Soil Nutrients

The wetland soil had a mean bulk density of 0.99 g cm^{-3} in the 0 to 10 cm

horizon and 1.30 g cm^{-3} in the 10 to 30 cm horizon. The percent organic matter was 8.9 and 7.9% for the 0 to 10 and 10 to 30 cm depths, respectively. This soil contained a total of 10500 kg N ha^{-1} and 83 kg P ha^{-1} in the top 30 cm of wetland soil. These values represent about 15 times more N and eight times more P than the amount that entered the wetland through tile input flow during the year.

Table 2. Monthly inlet and outlet flow and P forms for wetland during the 1998 water year. Water year began 1 October and ended 30 September the following year.

Month	Inlet Dissolved Reactive P	Outlet Dissolved Reactive P	Outlet Organic P	Outlet Total P
	kg P ha^{-1}			
Oct	0.0	0.0	0.0	0.0
Nov	0.4	0.0	0.0	0.0
Dec	0.5	0.6	0.1	0.6
Jan	1.4	0.7	0.1	0.8
Feb	0.2	0.0	0.0	0.0
Mar	3.5	2.0	0.1	2.1
Apr	0.9	0.1	0.3	0.4
May	2.3	2.0	0.2	2.2
Jun	0.7	0.7	0.1	0.8
July	0.3	0.3	0.0	0.3
Aug	0.0	0.0	0.0	0.0
Sep	0.0	0.0	0.0	0.0
Sum	10.2	6.3	1.0	7.3

Plant Biomass

Total biomass estimates ranged from 12000 to 30000 kg ha^{-1} with maximum biomass occurring in September (Fig. 2A). Most of the total biomass was comprised of the below-ground portion (54 to 77% of the total biomass); biomass values for roots ranged from 6300 to 23000 kg ha^{-1}. This was similar to other studies where roots were the major biomass component of wetland systems (Saarinen 1996) and where the majority of roots were found in the top 30 cm of sediment (Edwards 1992, Hsieh and Yang 1992, Saarinen 1996).

Root biomass of wetland plants can play an important role in wetland function, especially NO_3^- removal, because they can provide denitrifiers with carbon through exudates (Carpenter and Lodge 1993), as well as from decay processes (Saarinen 1996, Francez 1995). Roots can also provide an oxygenated zone where NH_4^+ can undergo nitrification to NO_3^- (Reddy et al. 1989). Nitrate can then diffuse out of the root zone to the adjacent anaerobic sediments where denitrification can take place. In this way, roots of aquatic plants can indirectly increase the amount of N removed in constructed wetland systems.

Litter mass reached a maximum during July at 4000 kg ha^{-1} and then declined throughout the growing season to 1000 kg ha^{-1} in October (Fig. 2A), suggesting rapid decay. Litter can provide a substrate for bacteria and periphyton (Weisner et

al. 1994), which provides a mechanism for breakdown. Hill (1979) found breakdown of aquatic macrophytes to be rapid, with much of the loss occurring within the first eight days and 100% loss of C, N, and P within 50-64 days.

Above-ground biomass increased until August (5700 kg ha^{-1}) and then showed a slight decline in October, likely due to seed drop and senescence of some of the early season plants (Fig. 2A). Grass biomass was variable throughout the study with a range of 1300 to 3000 kg ha^{-1} (Fig. 3A). This variability was due to a change in grass species composition throughout the study period, possibly caused by changes in soil moisture and temperature. Sedge increased in biomass throughout the study from 500 kg ha^{-1} in May to 2100 kg ha^{-1} (October). The values for "others" biomass followed a similar pattern to the total above-ground biomass, reaching a maximum

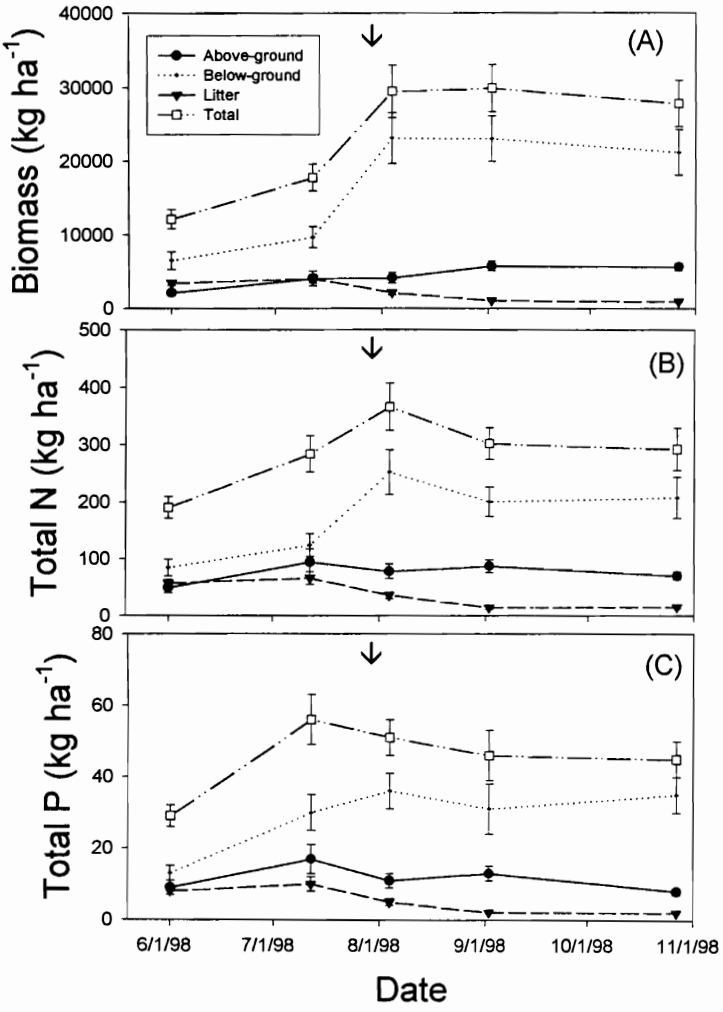

Figure 2. Biomass (A), total N (B), and total P (C) throughout the 1998 growing season (with standard errors). Above-ground includes all standing macrophytes and metaphytic algae. Below-ground includes all root material to a depth of 25 cm. Litter includes all plant material laying on the sediment surface. (↓denotes point at which the wetland dried down).

of 2500 kg ha^{-1} in September and then declining. The maximum "others" biomass corresponded with the natural drawdown, which exposed mudflats in the middle portion of the wetland. After the mudflats were exposed, there was rapid growth of annual species such as smartweed (*Polygonum punctatum*) and cocklebur (*Xanthium strumarium* L.). This finding is similar to Welling et al. (1988) who showed that mudflat annual recruitment was highest shortly after drawdown due to high soil moisture, moderate to high temperatures, and low soil conductivity. Algae were present only during the first two samplings, with biomass values of 230 and 103 kg ha^{-1}, respectively (Fig. 3A). After the wetland dried down there was no visible sign of algae, indicating rapid decomposition after the algae was deposited on the soil.

Eighteen species of macrophyte plants were found in the sampling plots during the study. Of these species, only four were found in each of the sampling periods,

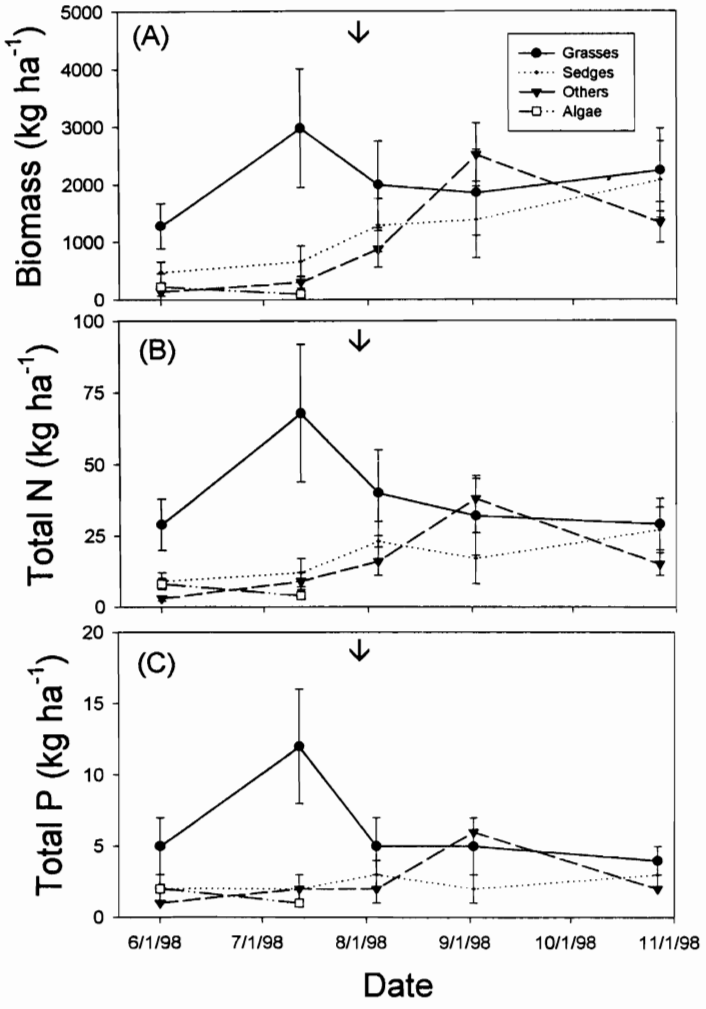

Figure 3. Biomass (A), total N (B), and total P (C) of above-ground macrophytes and metaphytic algae throughout the 1998 growing season (with standard errors). (↓ denotes the point at which the wetland dried down).

and they were the most abundant species overall (water smartweed, reed canary grass, sedge, and smartweed). At the beginning of the growing season, reed canary grass was the dominant species accounting for 46 and 70% of the total above-ground biomass during the first two sampling periods, respectively (Table 3). Smartweed was the dominant species in September. It underwent rapid growth following drawdown and had seed drop shortly after the September sampling. At the end of the growing season sedge became the dominant species with 37% of the aboveground biomass in October.

Table 3. Total above-ground macrophyte biomass (as a percent of total macrophyte biomass) of the four overall most abundant macrophyte species during the 1998 growing season.

Major Species						
		Sampling Period				
Common Name	Scientific Name	May-Jun	Jul	Aug	Sep	Oct
		Macrophyte Biomass (%)				
Water smartweed	*Polygonum amphibium*	2	6	6	12	5
Reed canary grass	*Phalaris arundinea*	46	70	41	23	25
Sedge	*Carex* spp.	25	17	26	23	37
Smartweed	*Polygonum punctatum*	2	2	14	28	17
All others	----------	26	6	12	13	16

Plant Nutrients

Total biomass N values increased to a maximum of 370 kg N ha^{-1} in August, with the following two sampling periods having a lower content (Fig. 2). Total biomass P content was greatest in July at 57 kg P ha^{-1} and then declined. The total N content for below-ground biomass followed the same pattern; below-ground total N was at a maximum in August with 250 kg N ha^{-1} and then slowly declined. This was the period of maximum recruitment of annual species, therefore, root establishment was also high. Following the August sampling period some of the early season perennial grasses had already undergone seed dispersal and were probably translocating nutrients back to the roots as part of senescence. The total P content for below-ground biomass also reached a maximum in August but remained generally steady with only a small decline through the remainder of the study. Above-ground N varied throughout the study period, ranging from 50 to 90 kg N ha^{-1} with a maximum in July. Above-ground P contents were also variable, ranging from 10 to 16 kg P ha^{-1} with the maximum value in July. Much of the above-ground variability in N and P content can be explained by the timing of maximum growth and seed drop for different plant species. Total N and total P contents for litter were greatest in July and then declined.

Although the nutrient content for below-ground biomass reached a maximum in August, the N and P tissue concentrations were the greatest in July during rapid growth (Fig. 4). Above-ground N and P tissue concentrations were also greatest in July and then declined. The high above-ground tissue concentrations corresponded to a period of rapid plant growth and seed development. Litter N and P concentrations remained nearly constant, although the amount of litter decreased throughout the study. This is consistent with other findings that N and P concentrations of litter remain nearly constant throughout the breakdown process (Hill 1979).

When the above-ground total N and total P were categorized by plant type, grasses had the greatest nutrient contents early in the season, with the maximum occurring in July (Fig. 3). High N and P standing stock corresponded to seed maturation in some of the major grass species occurring early in the study, whereas other secondary grass species flowered periodically throughout the study. Sedges were variable throughout the season, but attained maximum total N and total P content in October when sedge biomass was highest. The "others" total N and total P content increased to a maximum in September then declined. This is when mudflat annuals such as smartweed and cocklebur had reached maximum growth and seed maturation.

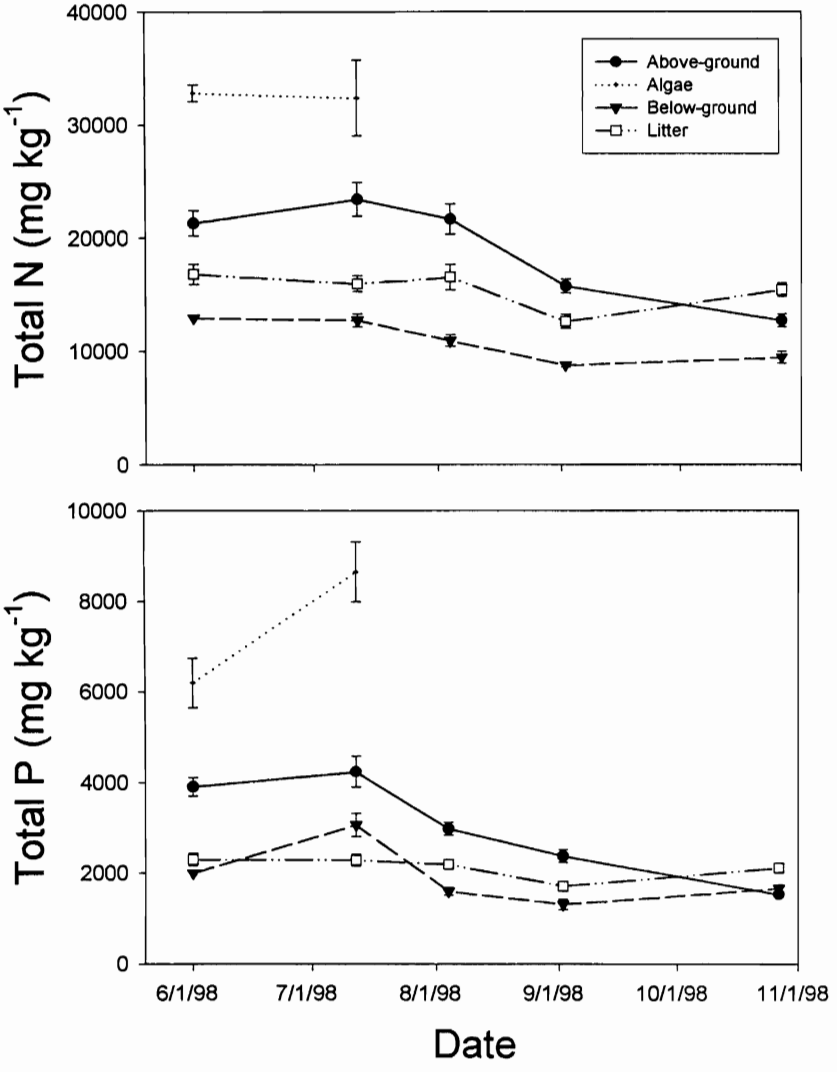

Figure 4. Nitrogen and P concentrations throughout the 1998 growing season (with standard errors). Above-ground includes all standing macrophytes. Algae includes all metaphytic algae. Below-ground includes all root material to a depth of 25 cm. Litter includes all plant material laying on the sediment surface.

Role of Plants in the Nutrient Budgets

Maximum plant biomass values were compared to input and output fluxes of N and P. Most of the inlet flow occurred in winter and early spring when little or no plant growth was occurring. Between the first and second sampling dates there was tile inlet flow and standing water, as well as active plant growth. During this period a net total (inlet minus outlet and seepage) of 57 kg N ha^{-1} was available to plants in the surrounding water of the wetland. Plants accumulated 93 kg N ha^{-1} during this same period, or 37 kg N ha^{-1} more than that accounted for in the water. Denitrification was also likely to take place during this time (Xue et al. 1999), further reducing water column N concentrations. This suggested that plants were getting much of their N from the sediments. A mesocosm study using ^{15}N in these same wetland systems (Xue et al. 1999) indicated that 90% of the N loss was by denitrification, and that plants retained about 10%. However, the biomasses in these mesocosm experiments were at significantly lower densities than were found in our study plots. This may indicate that higher plant N removal rates can be attained.

Plants constituted a large pool of N, but were overshadowed by a much larger pool of soil organic N (assuming most soil total N is in organic forms). Because some portion of the organic N undergoes mineralization and is then available for plant use, the need for uptake of N from the water column was probably minimal. Free-floating algal forms, however, must gain all of their nutrients from the water column. Due to the short period of time algae were present in this study, N accumulation by algae was limited (10 kg ha^{-1}). In years with a longer duration of wetland water throughout the summer, algae may contribute to greater accumulation of nutrients in biomass due to its high N and P concentrations.

The amount of P in plant material was much greater than the input from the tile, again suggesting that plants were taking up much of their nutrients from the sediments. The soil pool could have provided plants ample P to sustain growth without available P in the water column. Interestingly, an amount of P equal to the difference between the inlet and outlet P loads was accounted for in algae. However, some of the algae probably exited the wetland as organic P and the remainder likely decomposed after the wetland dried down and was incorporated into the soil P pool. The release of P from algae after decomposition might help to maintain the large P soil pools.

Wetland vegetation may not play a role in permanent nutrient removal from constructed wetland systems; however, it may act as a nutrient sink during periods of active growth. This study indicates that vegetation in constructed wetlands has the ability to acquire large amounts of nutrients. However, during periods of senescence wetland vegetation may become a source of nutrients to microbes and eventually to the surrounding water and sediments. Aquatic macrophytes provide a substrate for bacterial and periphyton growth (Brix 1997), leading to a possible increase in denitrification of nitrate in the surrounding water column. The periphyton can also supply organic carbon to the denitrifying bacteria, also enhancing denitrification.

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