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Nutrient Removal and Loading Rate Analysis of Louisiana Forested Wetlands Assimilating Treated Municipal Effluent

Rachael Hunter · Robert Lane · John Day · Joel Lindsey · Jason Day · Montgomery Hunter

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Abstract The relationship between nutrient removal and loading rate was examined using data from five forested wetlands in Louisiana that have received secondarily treated effluent from 3 to 60 years. Loading rates ranged from 0.65 to 26.80 g/m^2/yr for total nitrogen and 0.18 to 8.96 g/m^2/yr for total phosphorus. At loading rates below 20 g/m^2/yr, total nitrogen concentrations in surface waters of Louisiana forested wetlands were reduced to background concentrations (i.e., $\leq$3 mg/l). Similarly, at loading rates below 2 g/m^2/yr, total phosphorus concentrations were also generally reduced to background concentrations (i.e., $\leq$1 mg/l). These data demonstrate that freshwater forested wetlands can reduce nutrient concentrations in treated effluent to background concentrations present in relatively undisturbed wetlands. An understanding of the relationship between loading rates and nutrient removal in natural wetlands is important, particularly in Louisiana where discharges of fresh water are being used in ecosystem restoration.

Keywords Wetland assimilation · Treated effluent · Nutrient loading rate · Cypress-tupelo swamp · Wetland treatment

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R. Hunter (✉)
School of the Coast and Environment, Louisiana State University, Room 2239 Energy Coast and Environment Building, Baton Rouge, LA 70803, USA
e-mail: rhunter@lsu.edu

R. Lane · J. Day
School of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA

J. Lindsey · J. Day · M. Hunter
Comite Resources, Inc., Zachary, LA 70791, USA

Introduction

The ability of wetlands to remove nutrients from point-source discharge is primarily dependent on concentration and the area of wetland available to receive the effluent (Blahnik and Day 2000). These two variables, along with time, are integrated into the term 'loading rate', which is generally expressed as the amount of nutrient (e.g., nitrogen or phosphorus) introduced per unit area of wetland per unit time (e.g., g/m^2/yr). Loading rate into a wetland is inversely related to removal efficiency (RE), which is the percentage of a nutrient removed from the overlying water column and retained within the wetland ecosystem or released into the atmosphere (Blahnik and Day 2000). Richardson and Nichols (1985) demonstrated that nutrient RE is typically high at low loading rates (e.g., <25 g nitrogen/m^2/yr and <5 g phosphorus/m^2/yr) and decreases with an increase in loading rate (Fig. 1). Wetland assimilation systems in Louisiana typically have loading rates ranging from 2 to 15 g N/m^2/yr for total nitrogen (TN) and from 0.4 to 3 g P/m^2/yr for total phosphorus (TP; Day and others 2004) and, thus, according to the results of Richardson and Nichols (1985) nutrient removal should be >70% for TN and >60% for TP. Past performance of Louisiana assimilation wetlands has shown removal efficiencies for TN and TP at these loading rates range between 65 and 90%, while nitrate removal is usually between 90 and 100% (Zhang and others 2000; Day and others 2006; Brantley and others 2008).

In addition to providing municipalities with an economical means to meet water quality standards, adding nutrient rich secondarily-treated municipal effluent to hydrologically isolated and subsiding wetlands at low loading rates increases productivity, promotes vertical accretion, and buffers salt water (Rybczyk 1997; Rybczyk

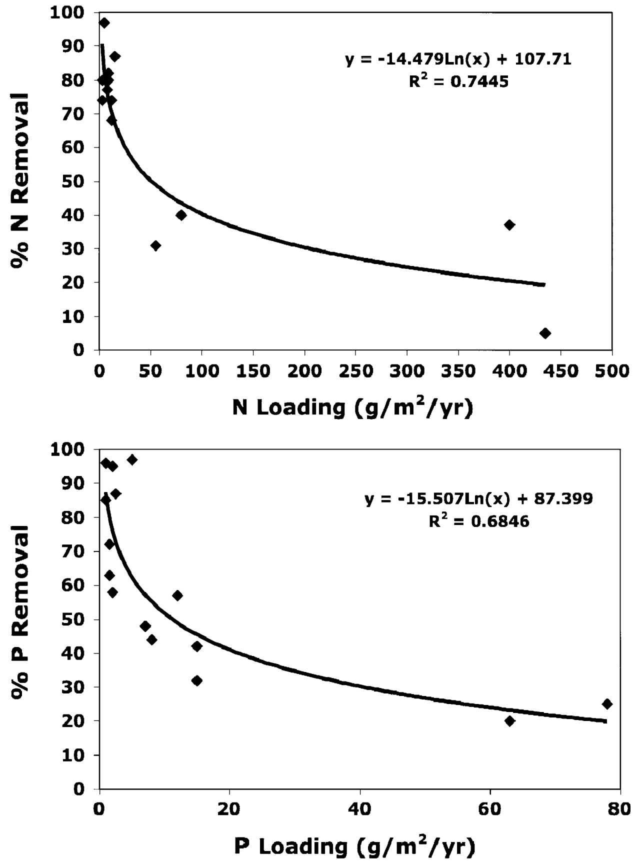

Fig. 1 Comparison of nitrogen (N) and phosphorus (P) removal with loading rate in wetlands. These graphs were redrawn from Richardson and Nichols (1985)

and others 2002; Day and others 2004, 2006). Since the early 1990s, scientists, regulatory personnel, and dischargers have worked closely to develop an approach where wetland assimilation systems meet water quality goals while protecting and restoring wetlands (Day and others 1999, 2004). Nutrients in treated effluent increase vegetative productivity (Hesse and others 1998; Rybczyk and others 1996; Day and others 2006), which helps offset regional subsidence by increasing organic matter deposition on the wetland surface and in the root zone (Rybczyk and others 2002; Brantley and others 2008). Because the effluent is a source of fresh water, it provides a buffer for saltwater intrusion events, especially during periods of drought, which are predicted to increase in frequency in mid latitudes in the future due to global climate change (IPCC 2001).

The objective of this article is to aggregate data from five natural forested wetlands receiving treated municipal effluent in Louisiana (termed assimilation wetlands) to investigate relationships between loading rates and removal efficiencies. An understanding of this relationship is needed because discharge of secondarily treated effluent into natural wetlands in Louisiana is becoming increasingly used as city managers realize the potential for low-cost water quality improvement and wetland restoration.

Methods

Study Sites

This study includes data for assimilation wetlands receiving discharge from the cities of Breaux Bridge, Hammond, Luling, Mandeville, and Thibodaux, Louisiana (Fig. 2). Hammond's assimilation wetland has the largest area and Mandeville's wetland has the smallest (Table 1). During the time of monitoring, loading rates ranged from 0.65 to 26.80 g/m^2/yr for TN and 0.18 to 8.96 g/m^2/yr for TP. At all sites, natural ridges and artificial barriers (e.g., spoil banks, roads, etc.) confine the discharge to the wetland and prevent short-circuiting of surface water flow. While hydraulic retention time (HRT) was not measured, it was estimated using water volume and wetland area. HRT is important to consider when discussing nutrient removal because it describes the amount of time the surface water is in the wetland and available for biogeochemical processes to affect N and P. Estimated HRT ranged from 77 days in the Mandeville wetland to 512 days in the Luling wetland (Table 1). The wetlands are described in more detail below.

The city of Breaux Bridge discharges into the Cypriere Perdue Swamp, a 1470-ha forested wetland located in St. Martin Parish, 3.5 km west of Breaux Bridge, Louisiana. The wetland is dominated by water tupelo (*Nyssa aquatica* L.), baldcypress (*Taxodium distichum* (L.) Rich.), red maple (*Acer rubrum* L.), black willow (*Salix nigra* Marsh.), and Chinese tallow (*Morella sebiferum* (L.); Hesse and others 1998). Secondarily-treated municipal effluent has been discharged into the wetland since the early 1950s. The city treatment system includes three oxidation ponds and a

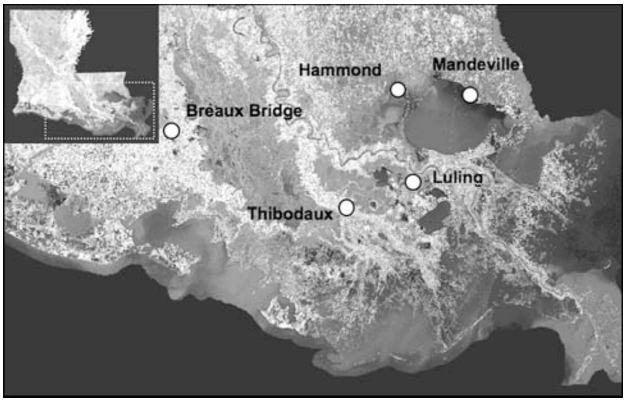

Fig. 2 Location of assimilation wetlands in southeastern Louisiana

Table 1 Mean Total Nitrogen (TN) and Total Phosphorus (TP) concentrations and TN and TP loading rates (±standard error) in wetland assimilation sites

Site	Years of data collection	Size (ha)	Mean TN in effluent (mg/l)	Mean TN loading rate (g/m^2/yr)	Mean TP in effluent (mg/l)	Mean TP loading rate (g/m^2/yr)	Estimated hydraulic retention time (days)
Breaux Bridge	2001–2008	1470	7.42 ± 0.82	0.65 ± 0.08	2.16 ± 0.21	0.18 ± 0.02	410
Hammond	2006–2008	4047	16.90 ± 1.72	2.10 ± 0.15	3.23 ± 0.66	0.39 ± 0.05	279
Luling	2006–2008	608	4.23 ± 1.06	1.65 ± 0.54	2.01 ± 0.16	0.68 ± 0.10	512
Mandeville	2002–2007	98	10.94 ± 3.39	26.80 ± 8.64	3.79 ± 0.19	8.96 ± 0.44	77
Thibodaux	2001–2008	300	14.44 ± 1.19	20.18 ± 1.74	1.52 ± 0.19	2.17 ± 0.33	158

chlorination/dechlorination system with the capacity to treat 3,785 m^3/day (1 million gallons per day). From 2000 to 2007, average monthly discharge into the assimilation wetland was 3,598 m^3/day and average concentrations of TN and TP were 7.42 and 2.16 mg/l, respectively.

The city of Hammond discharges into the South Slough wetland, located approximately 11.27 km southeast of Hammond, Louisiana. This wetland is dominated by baldcypress and water tupelo with freshwater marsh in the immediate discharge area. Surface water flows south into the Joyce Wildlife Management Area (4,047 ha) and then towards Lake Pontchartrain. Hammond's treatment system has a design capacity of 30,283 m^3/day and is a three-cell aerated lagoon. A wastewater distribution system disperses effluent evenly for 1.1 km along the northern edge of the wetlands. From 2006 to 2008, average discharge from the Hammond wastewater treatment plant (WWTP) into the assimilation wetland was 14,498 m^3/day, with average TN and TP concentrations of 16.90 and 3.23 mg/l, respectively.

The city of Luling assimilation wetland is a continuously flooded, freshwater forested wetland dominated by water tupelo and baldcypress. This 608-ha wetland is located to the east of the St. Charles Parish WWTP. The Luling treatment system consists of a facultative oxidation pond with ultraviolet disinfection. From 2006 to 2008, average discharge from the oxidation pond into the wetland was 5,943 m^3/day, with average TN and TP concentrations of 4.23 and 2.01 mg/l, respectively.

The city of Mandeville discharges into a 98-ha seasonally-flooded forest located along the meandering channel of Bayou Chinchuba near the city of Mandeville, Louisiana (Brantley and others 2008). The wetland is dominated by water tupelo, swamp blackgum (*Nyssa biflora* Walt.), and baldcypress. Mandeville has discharged treated effluent, with an average output of 7,196 m^3/day into Bayou Chinchuba wetland since 1998. The city's wastewater treatment process includes three aerated lagoon cells, a three-cell rock reed filter, and an ultraviolet disinfection system. From 2002 to 2007, average concentrations of TN and TP in treated effluent were 10.94 and 3.79 mg/l, respectively.

The city of Thibodaux discharges into the Pointe au Chene Swamp, a continuously flooded forest located about 10 km southwest of Thibodaux, Louisiana within a 1425-ha hydrologically restricted and subsiding basin (Rybczyk and others 2002; Zhang and others 2000). The 300-ha assimilation wetland is dominated by baldcypress, water tupelo, red maple, ash (*Fraxinus pennsylvanica* Marsh.), and black willow. Thibodaux has discharged secondarily-treated municipal effluent into the Pointe au Chene swamp since 1992. The city's treatment system consists of an aerated lagoon and a high-rate trickling filter. From 2001 to 2008, average discharge was 11,546 m^3/day, with average TN and TP concentrations of 14.44 and 1.52 mg/l, respectively (Day and others 2004).

Water Quality

Surface water was monitored at the effluent discharge pipe (PIPE) and at three areas within each assimilation wetland: (1) an area immediately adjacent to the point(s) of discharge (i.e., Treatment or TRT site); (2) the area where surface water leaves the wetland (i.e., OUT site); and (3) the area midpoint between the TRT and OUT site (i.e., MID site). A reference site (i.e., REF site) for each wetland was also established in a hydrologically separate, but ecologically similar, wetland located nearby.

Water quality was measured quarterly or bi-annually at sample sites described above. Discrete water samples were collected 5 to 10 cm below the water surface with effort taken not to stir bottom sediments or include any film present on water surface. The samples were immediately stored at 4°C, on ice, for preservation. Samples were analyzed for nitrate + nitrite (NO_x-N), ammonium (NH_4-N), total Kjeldahl nitrogen (TKN), ortho-phosphate (PO_4-P), total phosphorus (TP), and total suspended solids (TSS) by an EPA-approved laboratory in Baton Rouge, Louisiana, using EPA methods 300, 4500nh3c, 351.3, 300, 365.2, and 2540D, respectively. Total nitrogen (TN) concentration was either measured as TN using persulfate digestion or calculated by adding NO_x-N and TKN values. Organic nitrogen was calculated by subtracting NH_4 from TKN. Dissolved oxygen was also measured monthly in situ at each sample site within each treatment wetland using a Yellow Springs Instrument Co. meter. Length of sample collection for each site is noted in Table 1.

RE for a particular nutrient was calculated using equation (1) and is expressed as a percentage,

$$\mathrm{RE} = \left(\left(\mathrm{Conc}_{\mathrm{pipe}} - \mathrm{Conc}_{\mathrm{out}}\right)/\mathrm{Conc}_{\mathrm{pipe}}\right) * 100 \qquad (1)$$

where $\mathrm{Conc}_{\mathrm{pipe}}$ is the concentration of the constituent in treated effluent coming out of the discharge pipe and $\mathrm{Conc}_{\mathrm{out}}$ is the concentration in surface water at OUT site.

Statistics

Statistical analyses were carried out to determine differences in nutrient concentrations between sampling locations and assimilation wetlands. One-way analysis of variance was conducted using JMP® 7.0 statistical software (Sall and others 2005). An alpha probability level of <0.05 was used to define a significant difference. Replication occurred over time for each parameter at each site, thus allowing testing of differences between sites, independent of time or seasonality. Comparisons of means with significant ANOVA tests were made using Tukey-Kramer Honestly Significant Difference (HSD) test (Sall and others 2005).

Results

TN in effluent discharged from Hammond, Mandeville, and Thibodaux WWTPs was predominately (>50%) NO_x, while effluent from Breaux Bridge and Luling was composed of more organic nitrogen and NH_4^+ than NO_x (Fig. 3a). Concentrations of NO_x, NH_4^+, and organic nitrogen were much lower in the OUT and REF sites than in the PIPE at each wetland (Fig. 3b and c, respectively).

TN decreased as surface water moved through all the wetlands and concentrations were very similar at the OUT and REF monitoring sites. At the Hammond assimilation wetland, mean TN concentration decreased significantly from the PIPE to the OUT site ($P < 0.0001$), and was not significantly different between the OUT and REF sites (Fig. 4). Similar results were seen at the Breaux Bridge, Luling, and Thibodaux assimilation wetlands ($P < 0.0001$, 0.0375, 0.0001, respectively; Fig. 4). No significant differences were detected for TN among monitoring sites at the Mandeville assimilation wetland ($P < 0.0746$; Fig. 4).

Mean TP concentrations also decreased as surface water moved through the assimilation wetlands. At the Hammond, Breaux Bridge, Mandeville and Luling wetlands, mean TP concentrations significantly decreased from the PIPE to the OUT sites ($P < 0.0001$, 0.0001, 0.0002, and 0.0206, respectively) and no significant differences were detected between the OUT and REF sites (Fig. 4). At the Thibodaux assimilation wetland, no significant differences in mean TP concentrations were found among the PIPE, TRT, MID or OUT sites ($P < 0.0006$), but mean TP concentrations were significantly lower in the REF site compared to the other sites (Fig. 4).

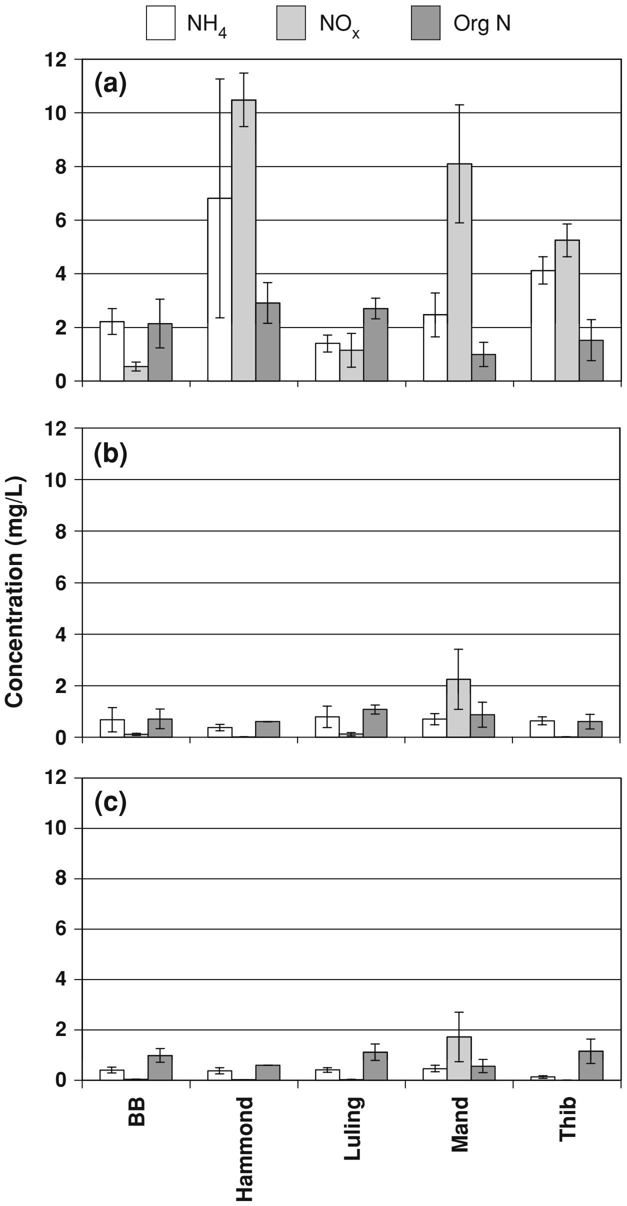

Fig. 3 Concentrations of ammonium (NH_4^+), nitrate + nitrite (NO_x), and organic nitrogen (Org N) in the PIPE (**a**), OUT (**b**), and REF wetland (**c**) for Breaux Bridge (BB), Hammond, Luling, Mandeville (Mand) and Thibodaux (Thib) assimilation wetlands. Error bars represent standard error. Nitrogen species concentrations do not add up to TN presented in Fig. 4 because nitrogen species data were not always available when TN concentrations were measured

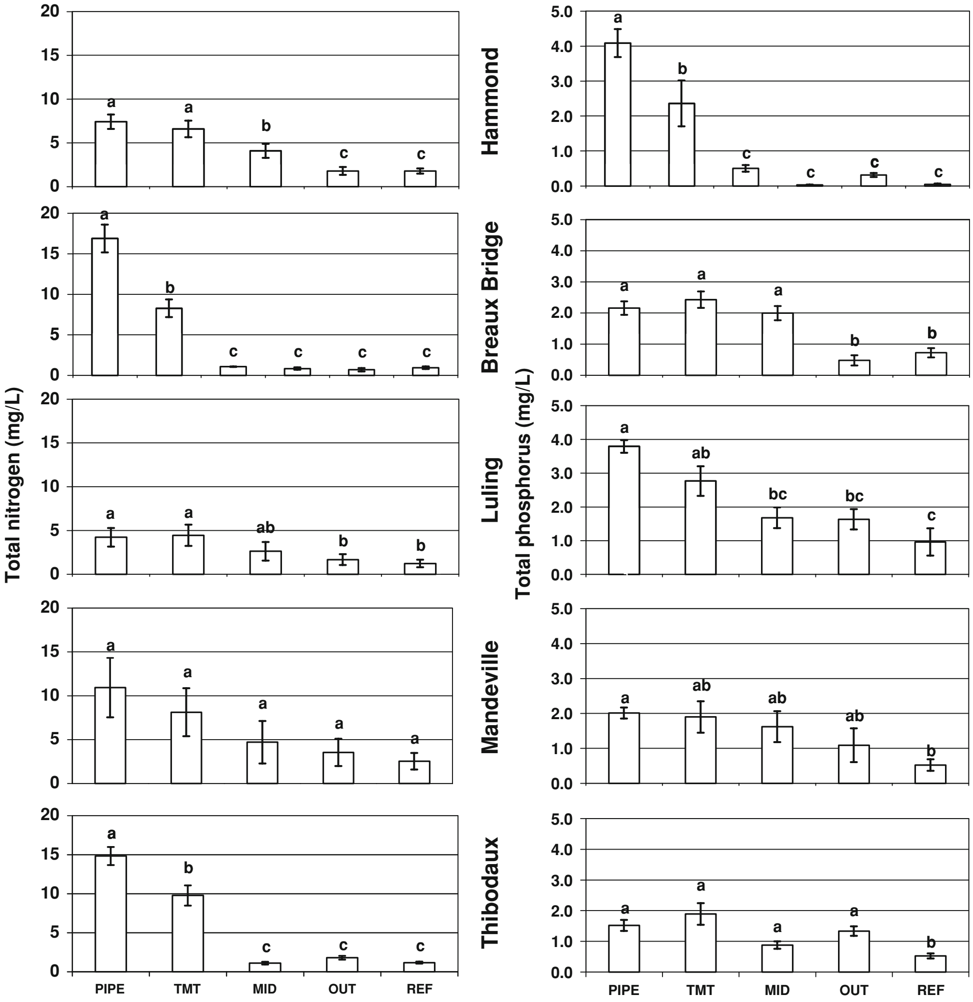

Fig. 4 Total nitrogen (TN) and total phosphorus (TP) concentrations in Hammond, Breaux Bridge, Luling, Mandeville, and Thibodaux assimilation wetlands. Error bars represent standard error. Concentrations with different letters are significantly different at an alpha = 0.05

Discussion

For the majority of samples analyzed, greater than 70% TN RE was calculated in the assimilation wetlands, regardless of loading rate (Fig. 5a). Mass balance calculations and isotopic analyses indicate that bacterial denitrification is the main mechanism for nitrogen removal from wetlands (Faulkner and Richardson 1989; Bachand and Horne 2000; Lund and others 2000). High rates of denitrification have been measured at the Thibodaux site (Crozier and others 1996; Boustany and others 1997). Denitrification rates can be increased by alternating oxidizing and reducing conditions (i.e., dry and flooded), which maximizes nitrification during aerobic periods and denitrification during anaerobic periods (Patrick and Wyatt 1964; Faulkner and Richardson 1989).

In addition to denitrification, nitrogen is also removed from the water column by plant uptake, incorporation into microbial cells during plant decomposition, and sorption of NH_4^+ onto organic matter and clay cation exchange complexes (Mitsch and Gosselink 2007; Kadlec and Wallace 2009). Another significant and permanent nutrient loss pathway is burial in wetland sediments, especially subsiding areas in coastal Louisiana (Day and others 2003). DeLaune and others (1981) estimated burial rates of 13–23 g N/m^2/yr and 0.8 g P/m^2/yr in Louisiana saltwater marshes. This pathway is particularly important in coastal Louisiana where subsidence in the Mississippi delta results in a relative sea level rise nearly 10 times greater than eustatic sea level rise (Conner and Day 1988; Penland and others 1988).

At Mandeville, there was no significant change in TN concentration among sites. This was most likely due to high loading rates (26.80 g N/m^2/yr) causing low RE and a relatively low estimated HRT compared to the other wetlands (Day and others 2004). To improve nutrient removal, the City of Mandeville is increasing the area of assimilation wetlands enough to reduce TN loading by approximately 60%. The rapid decline in RE with increasing loading may be due to limits on the rate of denitrification, such as the availability of labile carbon or NO_3, or from decreases in

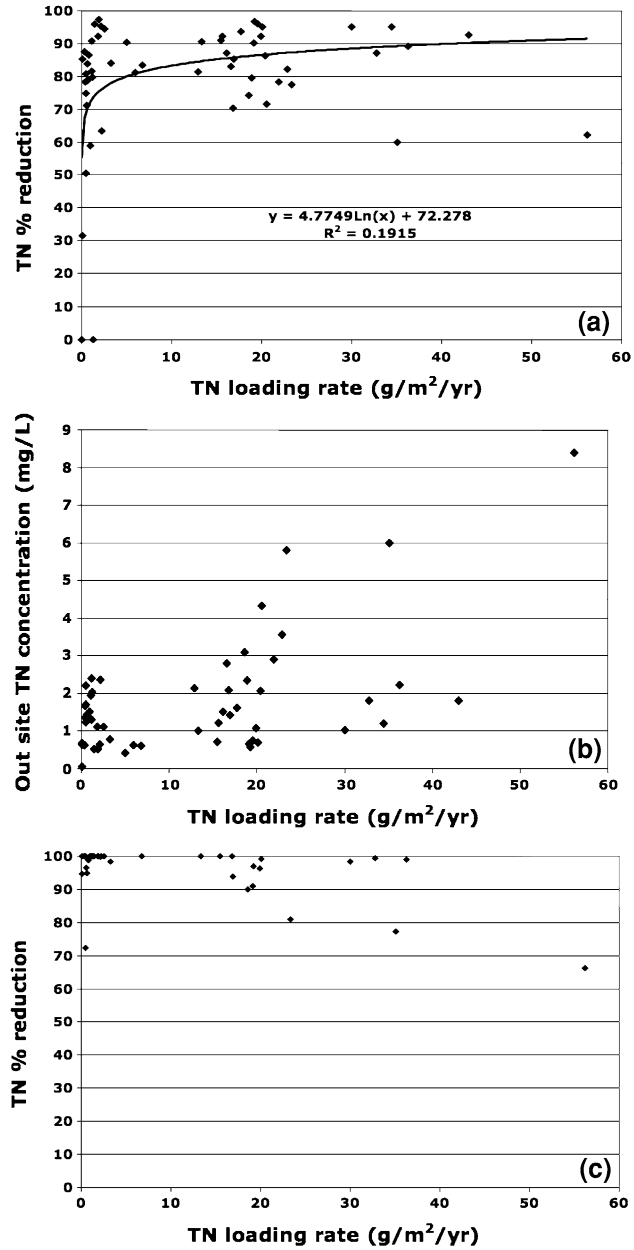

Fig. 5 Total nitrogen (TN) dynamics in assimilation wetlands: **a** TN removal efficiency in relation to loading rate; **b** TN concentrations in the OUT sites by loading rate; and **c** TN removal efficiency in relation to loading rate, using the reference site to calculate efficiency

HRT and/or the water-wetland interface due to increased water volume (Nichols 1983; Richardson and Nichols 1985).

According to the USEPA (2006), background conditions are the nutrient concentrations found in wetlands without anthropogenic additions. Mean TN concentrations were less than 3 mg/l at all the REF wetlands in this study (Fig. 4), suggesting the ambient background TN concentration to be $\leq$3 mg/l. Total nitrogen concentrations at the OUT sites of Breaux Bridge, Hammond, Luling, and Thibodaux were also less than 3 mg/l and not significantly different from respective REF sites, indicating that these wetlands are reducing TN to background levels (Fig. 5b).

If the surface water background concentration is 3 mg/l, then TN should not be reduced below this amount. Total nitrogen RE can then be re-calculated to account for background TN concentration using the following equation:

$$\mathrm{RE} = \left(\left(\mathrm{Mass_{pipe}} - \mathrm{Mass_{out}}\right) / \left(\mathrm{Mass_{pipe}} - \mathrm{Mass_{REF}}\right)\right) * 100 \qquad (2)$$

where $\mathrm{Mass_{pipe}}$ is the nutrient concentration of effluent at the point of discharge, $\mathrm{Mass_{out}}$ is the nutrient concentration where surface water leaves the assimilation wetland, and $\mathrm{Mass_{REF}}$ is the concentration in the reference wetland. When TN removal is re-calculated, RE is much greater (i.e., generally between 90–100%; Fig. 5c).

Breaux Bridge and Luling effluent contain a higher percentage of nitrogen bound in organic forms compared to effluent from Hammond, Thibodaux, and Mandeville. This is due to the lack of aeration in the retention ponds at Breaux Bridge and Luling. Wastewater treatment facilities at Hammond, Thibodaux, and Mandeville use treatment systems that produce a more nitrified effluent with higher NO_x concentrations than non-aerated ponds. Nitrogen RE is greatly enhanced when the predominate form of nitrogen in the overlying water column is NO_3, which is rapidly denitrified at the aerobic/anaerobic interface (Boustany and others 1997). Denitrification is a significant and permanent removal process for nitrogen in wetlands (DeLaune and others 1990, 1998, 2005; Boustany and others 1997; Hunter and Faulkner 2001; DeLaune and Jugsujinda 2003).

Total phosphorus removal was more variable than TN removal, with RE ranging from 0–100% at loading rates <10 g/m^2/yr (Fig. 6a). TP removal in wetlands is less predictable than TN because inorganic phosphate (PO_4), is readily sorbed by clay and detrital organic particles at high concentrations, while at lower concentrations PO_4 is released back into the water column, maintaining moderate ambient concentrations and providing a buffering mechanism for phosphorus (Jitts 1959; Patrick and Khalid 1974).

Total phosphorus concentrations decreased significantly at the Breaux Bridge, Hammond, Mandeville and Luling assimilation wetlands, with no significant differences detected between the respective OUT and REF sites, indicating reduction of TP to background concentrations. Mean TP concentrations at the REF sites were below 1 mg/l (Fig. 4), as were the majority of sample concentrations in the OUT sites at Breaux Bridge, Hammond, and Luling. Along with many of the phosphorus concentrations at Thibodaux, these data suggest a background TP concentration of $\leq$1.0 mg/l (Fig. 6b). Similar to removal of TN, TP removal improved when calculated using Eq. 2 (i.e., generally >60 percent at loading rates <10 g/m^2/yr; Fig. 6c).

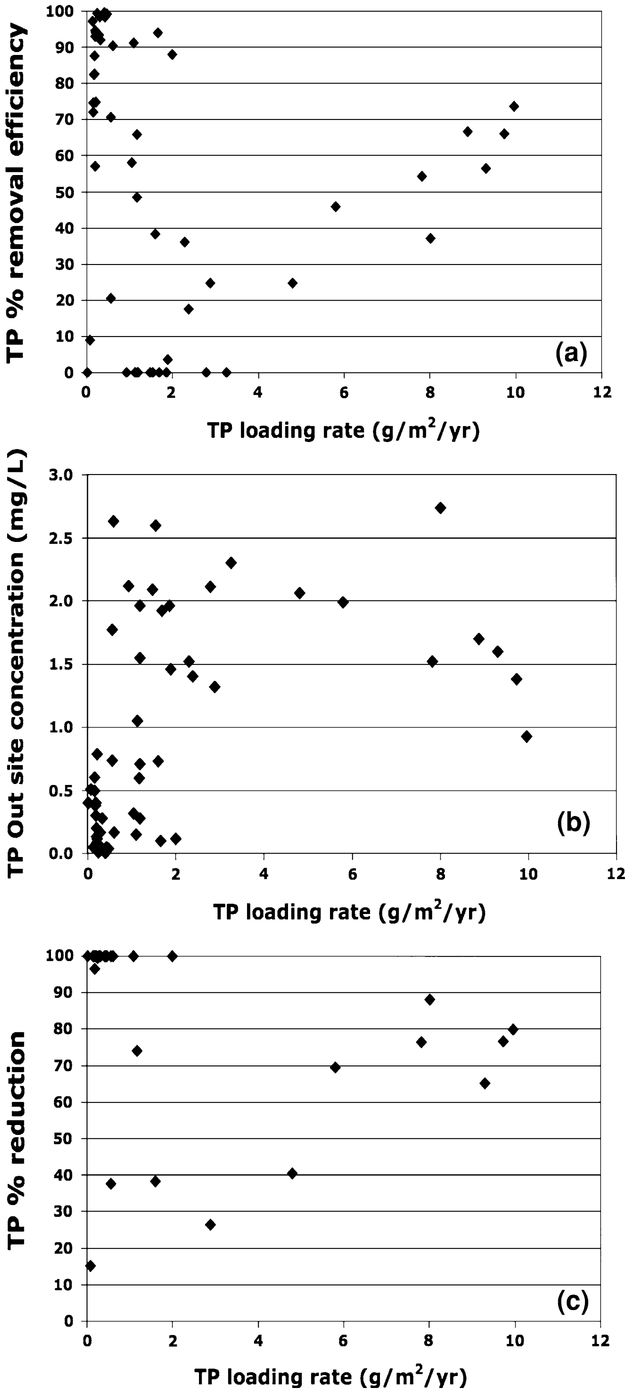

Fig. 6 Total phosphorus (TP) dynamics in assimilation wetlands: **a** TP removal efficiency in relation to loading rate; **b** TP concentrations in the OUT sites by loading rate; and **c** TP removal efficiency in relation to loading rate, using the reference site to calculate efficiency

The major mechanisms for removal of phosphorus from the water column in wetlands are plant uptake, microbial assimilation, and soil adsorption/sorption reactions (Patrick 1992). The most important factors determining phosphorus fixation and release in wetlands soils are the kinds and quantities of aluminum, iron, calcium, magnesium, and clay compounds, the oxidation-reduction status of the soil, and the soil pH (Nichols 1983; Patrick 1992). As with nitrogen, phosphorus removal can be optimized with alternating oxidized and reduced conditions, which recharge sorption sites in the soil and facilitates greater P removal than under permanently reduced conditions (Patrick 1992). The presence of submerged macrophytes also increases phosphorus retention through oxidation of the surface sediment layer, assimilation into plant material, and by promoting the settling of fine sediments and impeding the re-suspension or erosion of these sediments (Horppila and Nurminen 2003).

Some of the TP concentrations at the Thibodaux OUT site were higher than at Breaux Bridge, Luling, or Hammond, though loading rates were similar. This is most likely due to several factors. Mid-day dissolved oxygen concentrations were lower at Thibodaux (mean = 0.62 mg/l) compared to Mandeville (mean = 3.01 mg/l), Hammond (mean = 1.74 mg/l), Breaux Bridge (mean = 1.35 mg/l) and Luling (mean = 1.11 mg/l). Dissolved oxygen is an indicator of the aeration of the water column, which affects soils and the available surface area of ferrous compounds for sorption/desorption reactions (Patrick and Khalid 1974). Differences in hydrology could also be a factor since Thibodaux, Luling, and Mandeville were permanently flooded and Breaux Bridge and Hammond often dried annually. Decades of nutrient loading to wetlands can result in significant phosphorus accumulation in organic soil fractions due to phosphorus uptake by plants, which can then be released when soils are drained and oxidized (Bostic and White 2007). However, burial of phosphorus, as previously discussed, will permanently remove this nutrient. Breaux Bridge and Thibodaux have been assimilating treated effluent for decades while Hammond, Luling, and Mandeville have been receiving effluent for less than six years. Thibodaux has also been monitored for almost twenty years and more data exist for this site, which may show natural variations in precipitation and plant uptake. Thus, nutrient loading, permanent flooding, and anaerobic conditions that were greater in the Thibodaux wetland than in the Breaux Bridge, Hammond, and Luling wetlands may have caused more release of phosphorus into the overlying water column in the former wetland than the latter three wetlands, increasing TP concentrations.

Conclusions

At loading rates below 20 $g/m^2/yr$, total nitrogen concentrations in surface waters of Louisiana cypress-tupelo wetlands were reduced to background concentrations (i.e., ≤ 3 mg/l). Similarly, at loading rates below 2 $g/m^2/yr$

in the Hammond, Luling, and Breaux Bridge wetlands, total phosphorus concentrations were also reduced to background concentrations (i.e., ≤ 1.0 mg/l). These results demonstrate that forested wetlands in Louisiana can effectively reduce nutrients in secondarily treated effluent. Thus, treated municipal effluent should be considered a valuable resource for use in wetland restoration. Wetland assimilation also provides a low cost, energy efficient method for achieving the goals of water quality treatment. With forecasts of increasing energy scarcity and rising sea levels, sustainable methods for water quality treatment and ecosystem restoration are becoming increasingly valuable.

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