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Nitrate-nitrogen retention in wetlands in the Mississippi River Basin

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Abstract

Nitrate-nitrogen retention as a result of river water diversions is compared in experimental wetland basins in Ohio for 18 wetland-years (9 years × 2 wetland basins) and a large wetland complex in Louisiana (1 wetland basin × 4 years). The Ohio wetlands had an average nitrate-nitrogen retention of 39 g-N m^{-2} year^{-1}, while the Louisiana wetland had a slightly higher retention of 46 g-N m^{-2} year^{-1} for a similar loading rate area. When annual nitrate retention data from these sites are combined with 26 additional wetland-years of data from other wetland sites in the Basin Mississippi River (Ohio, Illinois, and Louisiana), a robust regression model of nitrate retention versus nitrate loading is developed. The model provides an estimate of 22,000 km^2 of wetland creation and restoration needed in the Mississippi River Basin to remove 40% of the nitrogen estimated to discharge into the Gulf of Mexico from the river basin. This estimated wetland restoration is 65 times the published net gain of wetlands in the entire USA over the past 10 years as enforced by the Clean Water Act and is four times the cumulative total of the USDA Wetland Reserve Program wetland protection and restoration activity for the entire USA.

Keywords: Wetland; Mississippi River Basin; Restoration; Olentangy River Wetland Research Park

1. Introduction

Humans have increased reactive nitrogen production, much of which becomes biologically available nitrogen, by over an order of magnitude from 1860 to 2000 (15–165 Tg/year), mainly due to fertilizer production, increased use of nitrogen-fixing organisms and fossil fuel combustion (Vitousek et al., 1997; Galloway et al., 2003). Significant amounts of this excess nitrogen are transported as nitrate-nitrogen to rivers and streams, leading to eutrophication and episodic and persistent hypoxia (dissolved oxygen < 2 mg/L) in coastal waters worldwide (NRC, 2000). For example, the Gulf of Mexico hypoxia in North America routinely reaches an extent of 20,000 km^2 (Rabalais, 2002; Rabalais et al., 2002; Scavia et al., 2003; Fig. 1). The connection between this hypoxia and the nitrate-nitrogen released from

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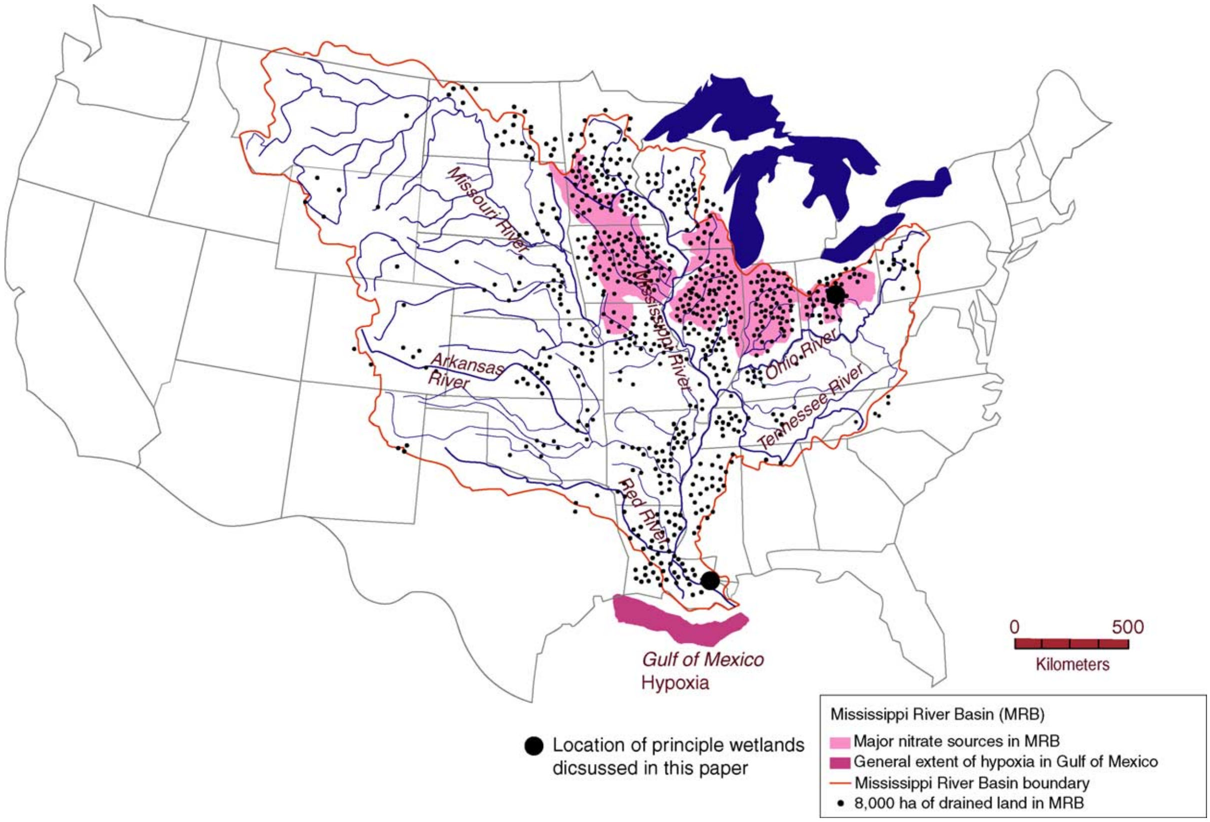
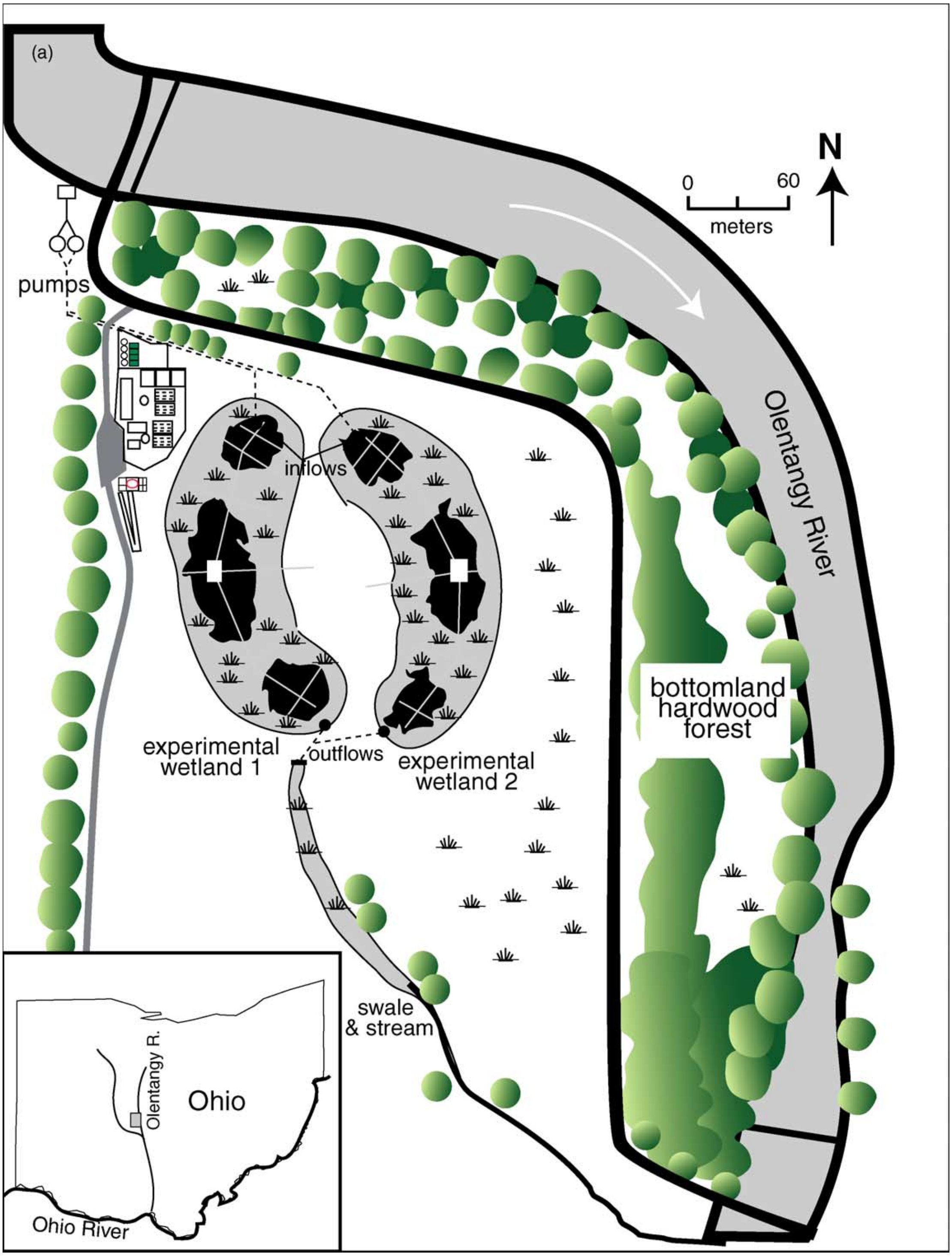


Fig. 1. Mississipi River Basin in the United States, showing location and general extent of Gulf of Mexico hypoxia in Louisiana coastline, high nitrogen loadings in the basin (>1000 kg-N km^{-2} year^{-1}; *source:* Goolsby et al., 1999), major historical drainage in the Basin (*source:* Mitsch and Gosselink, 2000) and wetland sites discussed in this paper (Large black circles).

the 3 million km^2 Mississippi River Basin is well established (Goolsby et al., 1999; McIssac et al., 2002; Rabalais et al., 2002; Scavia et al., 2003). The hypoxia of the Gulf of Mexico is also related to the large loss of wetlands in the Basin (Fig. 1) and to the separation of the Mississippi River from its floodplain and deltaic plain (Dahl, 1990; Mitsch et al., 2001; Day et al., 2003).

Three general approaches for reducing agriculturally derived nitrogen that would otherwise reach the Gulf of Mexico are (Mitsch et al., 2001): (1) change farming practices to minimize nitrate loss by reducing the use of nitrogen fertilizer and through a suite of management practices, (2) intercept laterally moving groundwater and surface water with nitrogen-sink ecosystems, particularly riparian zones and created and restored wetlands and (3) provide a system of river diversion backwaters along rivers and in the Mississippi River delta for interception of large fluxes of nitrogen associated with flood events. This paper concerns the efficacy of the second and third options and presents long-term data records that establish similarities in function of wetland retention of nitrate-nitrogen at different scales and climates in the Mississippi River Basin. Wetlands and riparian ecosystems can serve

Fig. 2. Two wetland research locations discussed in detail in this paper: (a) two 1-ha experimental wetlands at Olentangy River Wetland Research Park, Columbus, Ohio and (b) Caernarvon diversion to Breton Sound at Mississippi River in Louisiana (shading indicates area of most significant influence of diversion). Sampling locations in (a) were at the inflow to experimental wetland 1 (since the same water was delivered to each wetland) and at the outflows of wetlands 1 and 2. Sampling stations in (b) were at various locations southeast of the diversion and toward Breton Sound.



(a)
N
0
60
meters
pumps
inflows
Olentangy River
bottomland
hardwood
forest
experimental
wetland 1
outflows
experimental
wetland 2
swale
& stream
Olentangy R.
Ohio
Ohio River

as buffers between agricultural uplands and streams and rivers, particularly for excessive nitrate-nitrogen emanating from fertilizer use (Mitsch et al., 2001; Day et al., 2003). They can be designed in the landscape to enhance nitrate-nitrogen reduction through two main ecological processes: (1) denitrification and (2) nitrogen uptake by plants, microbes and macrophytes. The latter process is important if nitrogen is subsequently buried in the soil or if the plant material is permanently retained or harvested.

We first compare multi-year nitrate-nitrogen retention in river diversion wetlands at vastly different river

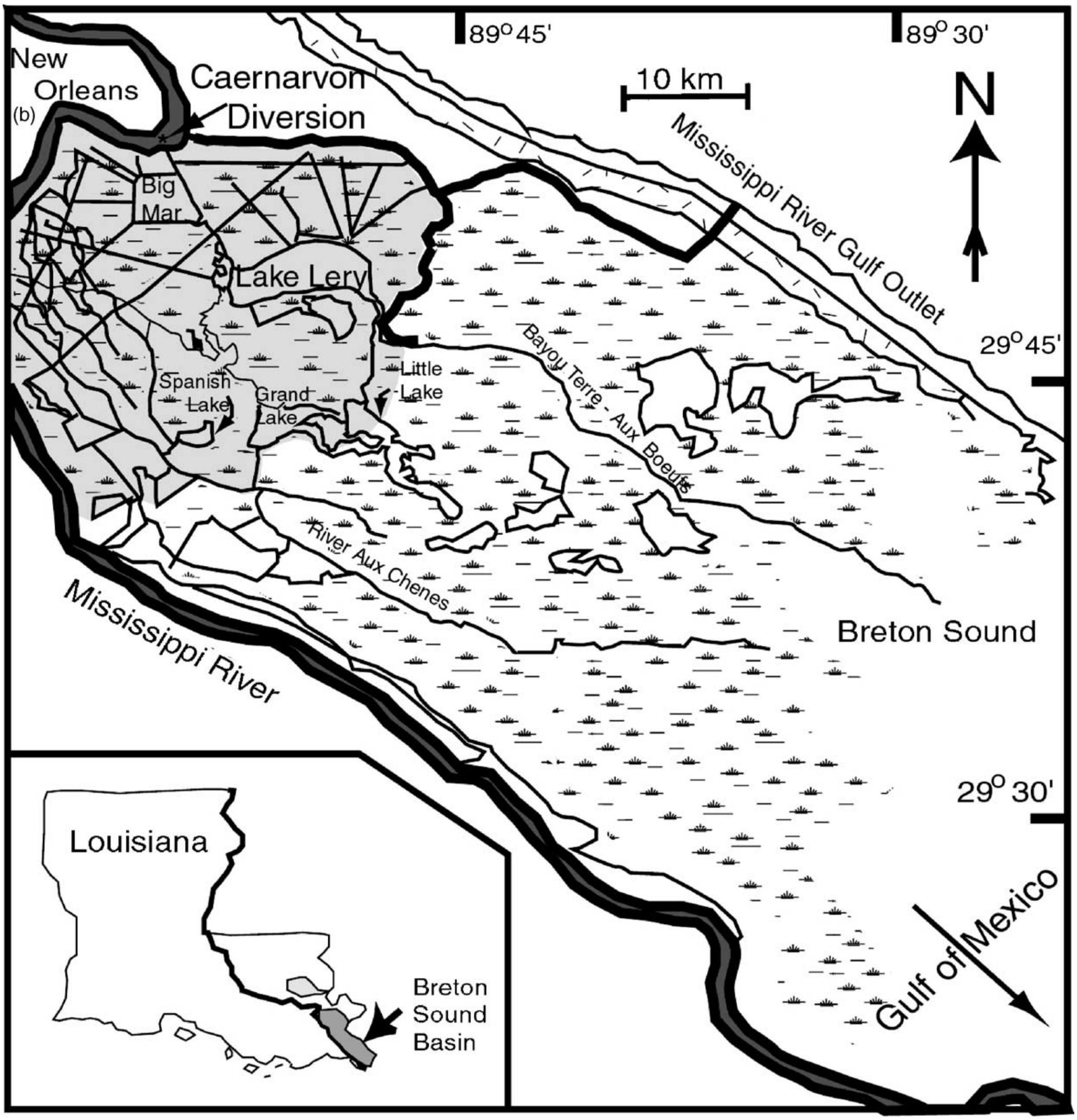


Fig. 2. (*Continued*).

scales—a fourth-order river in Ohio and the ninth-order lower Mississippi River at its delta in Louisiana. A river diversion wetland is a wetland on the adjacent floodplain or behind artificial levees that receives water by pumping or gravity flow from the main channel of a river and includes such floodplain features as oxbow lakes, backwater swamps and other riparian wetlands. Both the Ohio and Louisiana sites are part of the Mississippi River Basin that drains to the Gulf of Mexico (Fig. 1). Each riparian diversion system has been the site of significant research with similar sampling and analytical methodologies for several years. Each project involves diverting nutrient-laden riverine waters into adjacent riparian wetlands.

2. Materials and methods

2.1. Study areas

In Ohio, a pair of 1-ha experimental diversion wetlands basins were created in 1993 (Fig. 2a) and used in a whole-ecosystem wetland experiment from 1994 to 2003 (Mitsch et al., 1998, 2005; Mitsch and Jørgensen, 2004). Continuously pumped inflows have averaged 0.006–0.010 $m^3 s^{-1}$ (20–30 m $year^{-1}$) to each basin with day-to-day flow patterns corresponding to Olentangy River flow. The water passes through the wetlands in about 3–4 days and discharges to a common swale that in turn flows back to the Olentangy River.

In Louisiana, the diversion of the Mississippi River at Caernarvon (Fig. 2b) is one of the largest diversions in operation on the River aimed at restoring deteriorating wetlands in the Mississippi delta. The diversion structure on the east bank of the river south of New Orleans is a five-box culvert with vertical lift gates with a maximum flow of 280 $m^3 s^{-1}$. River diversion began in August 1991 and average minimum and maximum flows are 14 and 114 $m^3 s^{-1}$, respectively, with summer flow rates generally near the minimum and winter flow rates 50–80% of the maximum (Lane et al., 1999, 2004). The diversion delivers river water to the 260 km^2 Caernarvon freshwater wetland that eventually discharges into the brackish Breton Sound estuary, which is a part of coastal Gulf of Mexico.

In both cases, significant infrastructure (diversion gates, retention valves, plumbing and pumps) were used to control and measure flows into adjacent riparian wetlands. In both diversion systems, the wetlands are dominated by marshes, the percent macrophyte cover is similar at about 60% and net primary productivity at both sites is comparable.

2.2. Sampling and analysis

Weekly water samples were taken from the Olentangy River near the inflow pumps and at the inflow and outflows of the two experimental wetlands in Ohio for 9 years from 1994 to 2001 and 2003 (Fig. 1). Monthly water samples were taken along the major flow paths in the Caernarvon wetland in Louisiana from 1991 to 1994. Mississippi River nitrate data were collected and analyzed from 1988 to 1994 (7 years). During spring of 2001, an experimental large pulse of river water with a peak flow of 226 $m^3 s^{-1}$ was released through the Caernarvon structure for 16 days. Sampling was carried out during weekly transects from March 9 to 30, 2001. Discrete water samples were taken at 19 locations in the Breton Sound estuary, but only the five sampling locations closest to the diversion structure were used in this analysis (Lane et al., 2004).

Sample analysis at both sites was carried out using standard analytical methods (U.S. EPA, 1983, APHA, 1989, 1992). Water samples were collected in acid-washed bottles, filtered through 0.45 μm filters and frozen for later analysis of nitrate + nitrite ($NO_3 + NO_2$). Nitrate + nitrite were analyzed on a Lachat QuikChem IV automated system in Ohio and on a Alpkem autoanalyzer in Louisiana using the cadmium reduction method. Samples from April 1994 through July 1995 were run by similar methods by Heidelberg College Water Quality Laboratory using a Traacs 800 autoanalyzer. The accuracy of the nutrient analysis was checked every 10–20 samples with a known standard and the samples are redone if the accuracy was off by 5%.

Twice-daily (morning and evening) readings of both instantaneous and total integrated volume of pumping rates were collected by staff and students from the flow monitors in each pipe going to each Ohio wetland. Outflow measurements from the experimental wetlands are based on wetland water level and the status of the control weir boxes constructed at the southern edge of the basins. Manual readings of water level data were supplemented with continuous water level Ott Thalimedes data loggers installed in 2001 in each Ohio wetland basin.

2.3. Nutrient loading calculations

Nutrient loading rate (expressed as g-N m^{-2} $year^{-1}$) and removal efficiency (the percentage of nutrients removed from the water column based on both concentration and mass) were calculated for each wetland site in a similar manner.

Nutrient retention of nitrate was calculated using,

$$\text{Nutrient reduction (\% by mass)} = \left(\frac{Q_{in} - Q_{out}}{Q_{in}}\right) \times 100 \qquad (1)$$

where Q_{in} is the inflow flux of nitrate-nitrogen in the incoming river water and Q_{out} is the outflow flux of nitrate-nitrogen from the wetlands.

In Louisiana, since the wetland does not have a formal "basin" but rather extends eventually into Breton Sound and the Gulf of Mexico, the portion of wetlands between the Caernarvon Diversion structure and several water quality stations was used for calculating nutrient reduction (Lane et al., 1999). The effective area of wetlands was estimated to be 260 km^2. Two different datasets were used to analyze nitrate loading and retention at the Caernarvon diversion area: a monthly dataset from 1992 to 1994 (also analyzed by Lane et al., 1999) and a 1-year dataset with 15 sampling dates taken in 2001. Discharge from the Caernarvon diversion and NO_3 concentrations of incoming Mississippi River water were used to calculate nitrate-nitrogen inflow into the wetland. Two end-member stations were used in the 1992–1994 analysis and five were used with the 2001 dataset. Since water flows through two major routes (referred to as eastern and western), with approximately 66% of the flow being carried down the eastern route, the data were weighted accordingly to reflect the proportion of flow each route conveyed. The wetland areas used to calculate nitrate-nitrogen fluxes were 260 km^2 for the 1992–1994 data and 10, 30 and 50 km^2 for the 2001 data. Different areas were used in 2001 because of more detailed sampling at more sampling stations.

2.4. Data analysis

Statistical analyses were computed by SPSS 11.0 software, e.g. predictions for reduction% of NO_3 by concentration and mass versus inflow loading. A regression of curve estimation with logarithmic functions was used to generate predictions for % nitrate reduction with a 95% confidence interval.

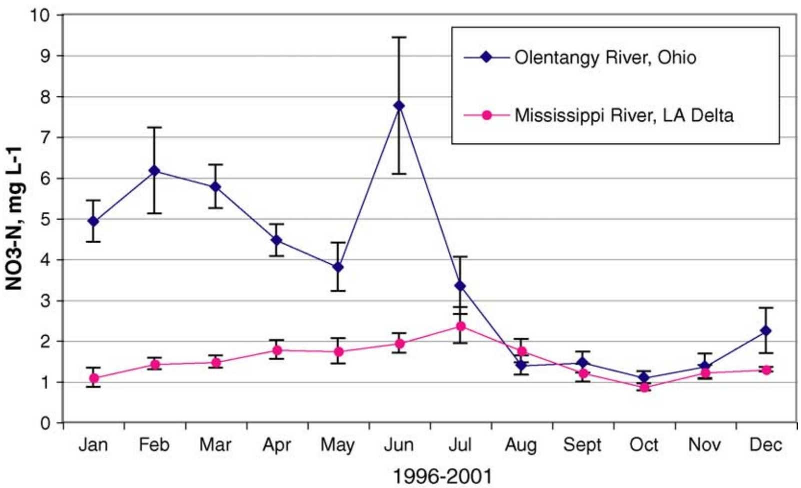


Fig. 3. Nitrate-nitrogen concentrations (average ± S.E.) in Olentangy River, Ohio and Mississippi River, Louisiana. Data for Olentangy River in Columbus are based on 8 years of weekly sampling; data from Mississippi River are based on 7 years of monthly sampling at Caernarvon, Louisiana.

3. Results and discussion

3.1. Patterns of nitrate-nitrogen in the rivers

Nitrate-nitrogen patterns in the Olentangy River in Ohio and Mississippi River in Louisiana are different in the "wet season" of January through June and similar in the "dry season" of late summer and autumn (Fig. 3). The Olentangy River, which is fed by an agricultural and urban watershed, has NO_3-N concentrations of 4–6 mg-N L^{-1} in the spring. The multi-year Olentangy River data reflect the general pattern of nitrate-nitrogen in Midwestern rivers, when peak concentrations are usually coincident with the first sustained precipitation events after fertilizer is applied in the spring (Randall et al., 1997; Goolsby et al., 1999; Mitsch et al., 2001). A peak with a large variability occurs in June when 63% of the weekly measurements over 6 years were greater than 5 mg-N L^{-1}. Nitrate concentrations in the lower Mississippi River near the Caernarvon diversion rise from a low of 1 mg-N L^{-1} in late fall and early winter to about 2 mg-N L^{-1} during high-flow conditions in late spring. Concentrations of nitrate-nitrogen in the Olentangy and Mississippi Rivers are remarkably similar from August through November.

3.2. Comparison of Ohio and Louisiana wetland nitrate retention

To compare the two-wetland sites given their different flow rates and vastly different sizes, inflows were normalized for the size of the wetland, i.e., areal loading rates and retention rates were calculated (Table 1). For 18-wetland-years of measurements (2 wetlands × 9 years), the Ohio wetlands retained an average of 35 ± 2% of nitrate-nitrogen by concentration

Table 1
Nitrate-nitrogen inflow, outflow and retention (by mass and concentration) for Olentangy River diversion wetlands in Ohio and Carenarvon River diversion wetlands in Louisiana

Wetland	Inflow g-N m^{-2} $year^{-1}$	Outflow g-N m^{-2} $year^{-1}$	Retention g-N m^{-2} $year^{-1}$	Mass retention (%)	Concentration retention (%)
Olentangy River wetlands, Ohio					
1994 Wetland 1	57.2	41.6	15.7	27	49
1994 Wetland 2	57.9	45.2	12.7	22	46
1995 Wetland 1	85.8	67.9	17.8	21	36
1995 Wetland 2	85.8	59.9	25.9	30	42
1996 Wetland 1	58.4	39.1	19.3	33	33
1996 Wetland 2	58.5	43.5	15.0	26	25
1997 Wetland 1	211	130	81	38	17
1997 Wetland 2	215	124	91	42	18
1998 Wetland 1	136	95	41	30	33
1998 Wetland 2	138	83	55	40	39
1999 Wetland 1	78.6	57.3	21.3	27	30
1999 Wetland 2	81.9	51.0	30.9	38	33
2000 Wetland 1	129.3	81.2	48.1	37	34
2000 Wetland 2	128.4	80.0	48.4	38	44
2001 Wetland 1	112.2	63.1	49.1	44	35
2001 Wetland 2	106.2	68.9	37.3	35	23
2003 Wetland 1	104.9	62.3	42.6	41	41
2003 Wetland 2	98.7	47.5	51.2	52	44
Caernarvon diversion, Louisiana					
1992[a]	5.60	0.17	5.43	97	97
1993[a]	7.30	1.54	5.76	79	79
1994[a]	12.7	4.2	8.5	67	67
2001[b]	50	19	31	62	62
2001[b]	84	38	46	55	55
2001[b]	251	161	90	36	36

[a] Based on effective Caernarvon wetland area of 226 m^2.
[b] Calculated on basis of Caernarvon wetland area of 10, 30 and 50 km^2 for the 2001 data.

and 35 ± 2% by mass. Our records showed that, overall, there a variability in concentrations of nitrate-nitrogen in the Olentangy River. In years of relatively high nitrate concentration (1996, 1997 and 2000), nitrates decreased from approximately 4.6–4.9 mg-N L^{-1} to 2.4–3.5 mg-N L^{-1} in the 1-ha wetlands. In a low-nitrate concentration year (e.g., 1999), nitrates decreased from approximately 2 to 1.3 mg-N L^{-1}.

By contrast, the Caernarvon wetland retained 39–92% of nitrate by mass and concentration, depending on the sampling location (Table 1). At the Caernarvon Louisiana sampling station that was most comparable to the Ohio wetlands for loading rates (station at 30 km^2, where loading rate is 84 g-N m^{-2} $year^{-1}$ compared to an average loading rate at the Ohio wetlands of 108 ± 11 g-N m^{-2} $year^{-1}$), the nitrate-nitrogen retention was 55% by mass and concentration (Table 1). The Olentangy River wetland site in Ohio averaged 35% retention by mass and concentration, considerably less retention. The Ohio wetlands

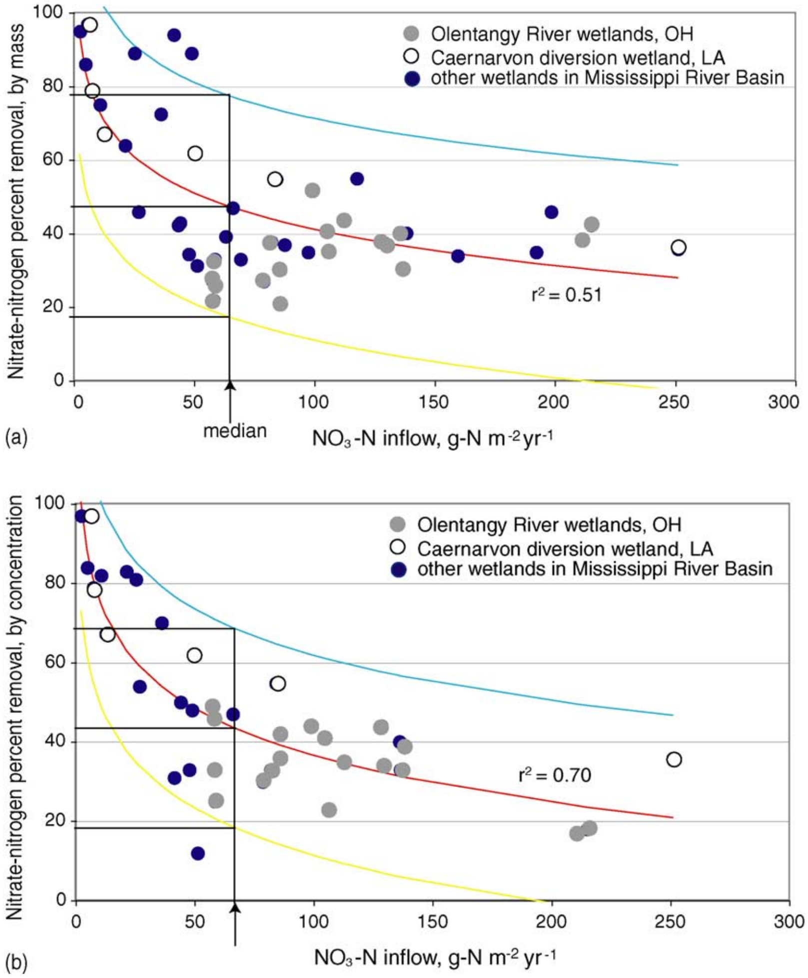


Fig. 4. Decrease in nitrate-nitrogen by (a) mass and (b) concentration for created and managed wetlands in Mississippi River Basin. Each data point represents data for a complete year for a wetland except for Caernarvon 2001data, which are based on 1-year of data (2001) and different "wetland basin" areas. Data from Olentangy River wetlands in Ohio and Caernarvon wetlands in Louisiana are supplemented by data from other wetlands studies in Ohio (Fink and Mitsch, 2004), Illinois (Kovacic et al., 2000; Phipps and Crumpton, 1994) and Louisiana (Lane et al., 2002). Outside lines are 95% confidence intervals. Vertical lines in graphs (a) and (b) indicate median loading rate of 60 g-N m^{-2} $year^{-1}$ and three resulting horizontal lines indicate median removal bracketed by the 95% confidence intervals used for predicting required area of wetlands.

had an average mass retention of 39 g-N m^{-2} year^{-1}, while the Louisiana wetland had a slightly higher retention of 46 g-N m^{-2} year^{-1} for a similar loading rate area. We believe that the more subtropical climate in southern Louisiana compared to the continential temperate climate in central Ohio is conducive to higher rates of denitrification and nutrient uptake because of higher water temperatures and a longer growing season.

3.3. Nitrogen retention model

A model of nitrate-nitrogen retention by wetlands in the Mississippi River Basin was developed combining the above 24 wetland-years of nitrate-nitrogen data from Ohio and Louisiana with nitrate reduction data from another 26 wetland-years of data from additional wetlands in Ohio, Illinois and Louisiana (Phipps and Crumpton, 1994; Kovacic et al., 2000; Lane et al., 2002; Fink and Mitsch, 2004; Mitsch and Day, in press). The nonlinear regression model explains 51% of the variation between nitrate-nitrogen inflow per unit area and nitrate mass reduction in the wetlands (Fig. 4a) and 70% of the variation for predicting nitrate concentration reduction in wetlands (Fig. 4b). In all of these additional case studies, the wetlands received either river diversions or agricultural runoff and all had published annual data on retention. Data from more extensively studied wastewater treatment wetlands (e.g., Kadlec and Knight, 1996) were not included here as these wetlands usually involve much higher loading rates and concentrations of nitrogen and can have different nitrogen species dominating (e.g., ammonium-nitrogen rather than nitrate-nitrogen) than normally found in ambient river and agricultural runoff.

3.4. The scale of wetland creation and restoration needed

Based on the relationship between loading and retention rates for wetlands, we determined from 50 wetland-years of data from 12 independent wetland basins in the Mississippi River Basin in Fig. 4, we estimated the wetland area required to remove 40% of the nitrogen load to the Gulf of Mexico. We assumed a median inflow rate of 60 g-N m^{-2} year^{-1} (and hence from Fig. 4a a nitrate-nirogen retention rate of 48% or 29 g-N m^{-2} year^{-1}). Creation or restoration of 22,000 km^2 of wetlands in the Mississippi River Basin is estimated as the area required to remove 40% of the total nitrogen estimated by Goolsby et al. (1999) calculated as discharging to the Gulf of Mexico (total nitrogen flux to the Gulf of Mexico = 1,570,000 Mg-N year^{-1}). The calculation is shown as:

$$\text{Area required (km}^2\text{)} = \frac{1.57 \times 10^{12}(\text{g-N year}^{-1}) \times 0.40}{29(\text{g-N m}^{-2}\,\text{year}^{-1}) \times 10^6(\text{m}^2\,\text{km}^{-2})} = 22,000\,\text{km}^2$$

In order to attach a variance on this estimate, we developed a model that predicted the 95% confidence interval for the data as shown in Fig. 4a. Using that confidence interval with the same loading assumption, the amount of wetlands needed to reduce the load by 40% ranges from 13,000 to 58,000 km^2. The low area assumes a mass retention of 78% of nitrate-nitrogen in the wetlands and the high area assumes a mass retention of 18% of nitrate-nitrogen in the wetlands as shown in Fig. 4a.

Assuming the same inflow rate of nitrate-nitrogen as described above, our model predicts that the average wetland might be expected to reduce nitrate-nitrogen concentrations about 45%, with a 95% confidence interval between 19 and 68% reduction (Fig. 4b). Nitrate-nitrogen retention rates above 80% should not be expected unless inflow rates are a third of our design inflow rate of 60 g-N m^{-2} year^{-1}.

If bottomland hardwood riparian forests are used as “wetlands” in this management strategy, the area required for an equivalent nitrate-nitrogen reduction is probably more, as our analysis has shown that bottomland hardwood forests retain generally less nitrogen per unit area than do wetlands (Mitsch et al., 2001). Our 22,000 km^2 estimate is based on more complete wetland data than were available in the late 1990s and provides a more confident estimate of the required wetland area than an earlier estimate of 21,000–53,000 km^2 of wetlands recommended by us earlier (Mitsch et al., 2001). This ecologically engineered nitrogen reduction, combined with an estimated 20% nitrate reduction that we estimated could be done by appropriate agronomic practices would result in enough reduction in nitrates entering the Gulf of Mexico to ensure a significant decrease in the size of the Gulf of Mexico hypoxia. We base this conclusion on the fact that Brezonik et al. (1999) found a generally linear relationship between nitrate-nitrogen flux to the Gulf and the size of the hypoxia in the Gulf. An overall reduction of 60% of nitrate-nitrogen in the Mississippi River Basin due to agronomic and ecological means should reduce the hypoxia area by approximately 60%.

3.5. Comparing this restoration to other wetland restoration efforts

To put our wetland restoration recommendation of 22,000 km^2 in perspective, there has been an estimated net gain of only 336 km^2 of wetlands in the entire United States over the past decade (*source:* US ACOE 2003 data, personal communication) due to wetland mitigation and enforcement of the Clean Water Act. By contrast, under a USDA national conservation set-aside program in agriculture to restore and protect wetlands called the Wetland Reserve Program (WRP), it is estimated that farmers have restored about 6000 km^2 of wetlands in the United States though 2003 (*source:* Natural Resources Conservation Service 2004 web site: http://www.nrcs.usda.gov/programs/wrp/). Thus, an effort estimated to be 65 times current efforts of wetland restoration and creation in the entire United States through the Clean Water Act and 4 times current wetland restoration through the Wetland Reserve Program would be needed in the Mississippi River Basin alone to have a significant effect on the Gulf of Mexico hypoxia.

3.6. Wetlands and agriculture

Our recommendation of setting aside less than 1% or 22,000 km^2 of the 3,000,000 km^2 Mississippi River Basin as an ecological solution to the Gulf of Mexico hypoxia provides a reasonable alternative to a major reduction in fertilizer use that could reduce agricultural output and cause an economic impact in the basin. Doering et al. (1999) agreed with this assessment when they found that restoring 20,000 km^2 of wetlands in the Mississippi River Basin would have minimal impact on agricultural production in the basin. Furthermore, they argued that if nitrogen fertilizer use is restricted within the Mississippi River Basin, then the crop production and hence nitrogen pollution would simply be transferred to somewhere else. Our solution to the nitrate problem does not lead to the transfer of nitrate pollution to another watershed.

McIssac et al. (2002) suggested by retrospective analysis that a 33% reduction in nitrate-nitrogen in the basin could result from simply reducing nitrogen fertilizer use in the basin by 12%. We believe that this is a misleading interpretation that makes solving the problem appear to be much easier than it really is. There are uncertainties in the data as described in Goolsby et al. (1999) that were used in this analysis. Studies described by Randall et al. (1997) and Mitsch et al. (1999) in Minnesota and R. Turco (personal communication) in Indiana show a relative insensitivity of nitrate-nitrogen in the effluent of test agronomic plots to fertilizer use rates. For example, plot data in Minnesota showed that, "if the annual nitrogen fertilizer rate was reduced by about 10% to 125 kg-N/ha and no other nitrogen was applied, one could expect a small yield decrease and nitrate concentrations could be expected to decrease about 3 mg-N/L" (Mitsch et al., 1999). This was a relatively low (∼10%) decrease in nitrate-nitrogen in the effluent from these study plots. Both agronomic and ecological solutions are needed together for this large-scale pollution problem.

3.7. Benefits to the basin

The wetland creation and restoration suggested here is primarily for solving the problem of the Gulf of Mexico hypoxia off of the coast of Louisiana. But the wetland restoration recommended in our paper would also provide other ecological services locally in the upper Mississippi River Basin including restoration of wetland and riverine habitats and provision of flood mitigation, both of which are very much needed in the Mississippi River Basin because of past wetland drainage in the Basin (Mitsch and Day, in press). The nitrate-nitrogen reduction in Midwestern rivers caused by both wetlands and agronomic practices would also lessen public health concerns about nitrate-nitrogen in urban drinking water taken from Midwestern rivers.

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