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Improved nitrogen treatment by constructed wetlands receiving partially nitrified liquid swine manure

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Abstract

Denitrification is more desirable than ammonia volatilization for nitrogen removal from constructed wetlands treating animal manure but is limited by the availability of nitrate/nitrite. The research objective was to determine if partial nitrification of swine wastewater prior to wetland application affects the nitrogen removal and ammonia volatilization from constructed wetlands. From September 2000 through November 2001, partially nitrified and unaltered swine wastewater from an anaerobic waste lagoon were applied to two parallel sets of constructed wetlands (3.6 × 67 m) in North Carolina, USA. Constructed wetlands were more efficient at removing total nitrogen from partially nitrified (64 and 78%) than from unaltered wastewater (32 and 68%). Both wetlands were effective in removing nitrate/nitrite from partially nitrified wastewater. However, the *Schoenoplectus*-dominated wetland was more effective than the *Typha-Echinochloa* dominated wetland in removing total (85 vs. 61%) and ammoniacal nitrogen (91 vs. 52%) from both types of wastewater. Only one of eight tests showed significant evidence of ammonia volatilization (2.1 mg nitrogen m^{-2} h^{-1}) when the wastewater was partially nitrified. A correlation ($r^2 = 33\%$) between ammonia-nitrogen volatilization and ammoniacal nitrogen concentration suggested that partial nitrification reduced ammonia volatilization because it lowered ammoniacal nitrogen of the wastewater.

Keywords: Ammonia volatilization; Nitrification; Constructed wetlands; Swine manure

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1. Introduction

The growing number and size of concentrated animal operations in the US make the treatment of manure generated by these operations of increasing public concern. This is particularly true in North Carolina, one of the larger pork producing states, where animal manure has impacted water quality (Mallin, 2000). Manure generated by concentrated swine operations is commonly stored in and partially treated by anaerobic lagoons, and the liquid manure from the lagoon is sprayed on nearby fields planted with either row or forage crops. If nutrients in this wastewater are applied at

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rates in excess of crop uptake rates, the excess nutrients may enter surface and groundwater due to runoff and leaching (Stone et al., 1998). To reduce the nutrient load to the environment, alternate or additional forms of wastewater treatment should be implemented. One option for additional treatment is to use a constructed wetland to reduce the nutrient concentration of swine wastewater prior to land application.

Constructed wetlands are appealing options for additional treatment because they provide an operationally passive form of wastewater treatment (Hunt and Poach, 2001; Kadlec and Knight, 1996). Also, constructed wetlands can effectively treat large quantities of animal–manure inflows (Knight et al., 2000). This is especially true for the treatment of nitrogen. For example, constructed wetlands in North Carolina removed 70–95% of nitrogen from swine wastewater when they received nitrogen loads between 3 and 36 kg ha^{-1} per day (Hunt et al., 2002a).

Wetlands remove nitrogen from wastewater by sedimentation, adsorption, organic matter accumulation, microbial assimilation, nitrification–denitrification, and ammonia volatilization (Brix, 1993; Johnston, 1991). Nitrification–denitrification is the preferred mechanism for nitrogen removal because it permanently removes nitrogen by converting ammonia predominantly to dinitrogen. Ammonia volatilization is undesirable because ammonia is an atmospheric pollutant that can also pollute terrestrial and aquatic environments through dry and wet deposition (Asman, 1994).

Denitrification in constructed wetlands treating swine wastewater is nitrate limited (Hunt et al., 2002a, 2003; note: in this article, "nitrate" denotes both nitrate and nitrite). This implies that nitrification, the conversion of ammoniacal nitrogen to nitrate, prior to wetland application should enhance nitrogen removal by these constructed wetlands because it will increase the nitrate available for denitrification. An increase in the rate of nitrogen removal means that the nitrogen-loading rate to the wetland can be increased or that the wetland area needed to treat swine wastewater can be decreased.

Research conducted on constructed wetlands treating swine wastewater found that ammonia volatilization accounted for less than 20% of the nitrogen removed by the wetlands (Poach et al., 2002). Therefore, in contrast to Payne and Knight (1997), ammonia volatilization did not dominate nitrogen removal from these constructed wetlands, but it still constituted a pollution concern. If possible, constructed wetlands receiving liquid animal manure should be managed to reduce ammonia volatilization especially when they are used in conjunction with alternative treatment systems that are designed to prevent ammonia emissions, such as lagoon-less or covered-lagoon systems. Pre-wetland nitrification may reduce ammonia volatilization because it reduces the wastewater ammoniacal nitrogen concentration. At high nitrogen loads, the reduction of wastewater ammoniacal nitrogen provides the added benefit of reducing the potential for ammonia toxicity to wetland plants.

Complete nitrification of swine wastewater may not be necessary to improve the treatment of nitrogen by constructed wetlands because the wetlands have an inherent ability to nitrify ammoniacal nitrogen. Partial nitrification of the wastewater may be all that is necessary to produce the desired improvements to nitrogen treatment by constructed wetlands. Partial nitrification would also benefit the farmer because its cost should be lower than the cost of complete nitrification.

This experiment was part of a long-term study of a constructed wetland complex in North Carolina used to investigate wetland treatment of lagoon wastewater from a confined swine operation. Past experiments have compared constructed wetland treatment at several different nitrogen and phosphorus loads and with different plant species (Hunt et al., 2002a, 1999). Other experiments have investigated the mechanisms for nitrogen removal such as ammonia volatilization and denitrification (Hunt et al., 2003; Poach et al., 2002). The present experiment was formulated based on the results of those prior experiments. The objectives of this experiment were to determine if the partial nitrification of swine wastewater prior to wetland application affects (1) the nitrogen removal efficiency of and (2) the ammonia volatilization from these particular constructed wetlands. Objectives were met by alternately loading the constructed wetlands with partially nitrified and unaltered wastewater and comparing the nitrogen budgets between treatments.

2. Materials and methods

2.1. Study location

The experiment was conducted during September 2000 through November 2001 on wetlands constructed at a swine farm in Duplin County, NC, USA. The farm includes a 2600-swine nursery. Manure generated by the swine was flushed from the houses to a single-stage anaerobic lagoon. During the experiment, the lagoon liquid contained an average 335 mg l^{-1} of total Kjeldahl nitrogen (TKN) (79% ammoniacal nitrogen), 119 mg l^{-1} of total phosphorus, and 1048 mg l^{-1} of chemical oxygen demand.

2.2. Constructed wetland design

The research site consisted of two parallel wetland systems, each of which had two 3.6 × 33.5 m cells connected in series (Fig. 1). The cells were built by soil excavation in 1992 (Hunt et al., 1994). Once the cells were excavated, the bottoms were graded to a 0.2% slope and sealed with a compacted clay liner. The clay liner was covered with a 0.25 m layer of loamy sand soil.

Wetland System 1 was planted with *Schoenoplectus tabernaemontani* (K.C. Gmel.) Palla (softstem bulrush), *Schoenoplectus americanus* (Pers.) Volkart ex Schinz & R. Keller (American bulrush), *Scirpus cyperinus* (L.) Kunth (woolgrass bulrush), and *Juncus effusus* L. (soft-rush). Wetland System 2 was planted with *Typha latifolia* L. (broadleaf cattail), *Typha angustifolia* L. (narrowleaf cattail), and *Sparganium americanum* Nutt. (American bur-reed). *Schoenoplectus* sp. and *Typha* sp. eventually dominated their respective systems. In May 2000, *Typha* sp. started to diminish in the first cell of Wetland System 1. By April 2001, *Typha* sp. still dominated the second cell, but a species of *Echinochloa* (barnyard grass) dominated the first cell. The cause of the shift in plant species has not been determined at this time.

2.3. Experimental design

Whereas only two systems were available and each was dominated by different plant species, it was necessary to apply each treatment successively to each wetland system to evaluate if pre-wetland nitrification of swine wastewater affects nitrogen removal by the constructed wetlands. Experimental design was further constrained because environmental conditions can affect both denitrification and ammonia volatilization. Therefore, it was necessary employ a crossover design for treatment application. Unaltered wastewater was applied to one wetland system at the same time partially nitrified wastewater was applied to the other system. Because each system needed to receive both treatments, the type of wastewater applied to each system was switched during the experiment. However, before initiating the new application scheme, each system received unaltered wastewater for 2 months to reduce the carryover effects from the prior wastewater application scheme.

Lagoon wastewater was initially pumped to a holding tank (Fig. 1). Peristaltic pumps then transferred wastewater from the holding tank to both the head of one wetland system and to a nitrification unit. Subsequently, nitrified wastewater was applied by gravity flow to the head of the wetland system scheduled to receive it. From September 2000 through April 2001, unaltered and nitrified wastewater were applied to Wetland System 1 and 2, respectively. From July through November 2001, the treatments were switched so unaltered and nitrified wastewater were applied to Wetland System 1 and 2, respectively. Unaltered wastewater was applied to both wetlands during the equilibrium period of May and June 2001. Wastewater inflow was originally set to load nitrogen at an approximate rate of 20 kg nitrogen ha^{-1} per day.

The nitrification unit consisted of a 0.34 m^3 contact aeration tank used to lower influent biochemical oxygen demand, followed by a 0.18 m^3 sedimentation tank, and a 1.3 m^3 aerated fluidized tank for nitrification. The nitrification

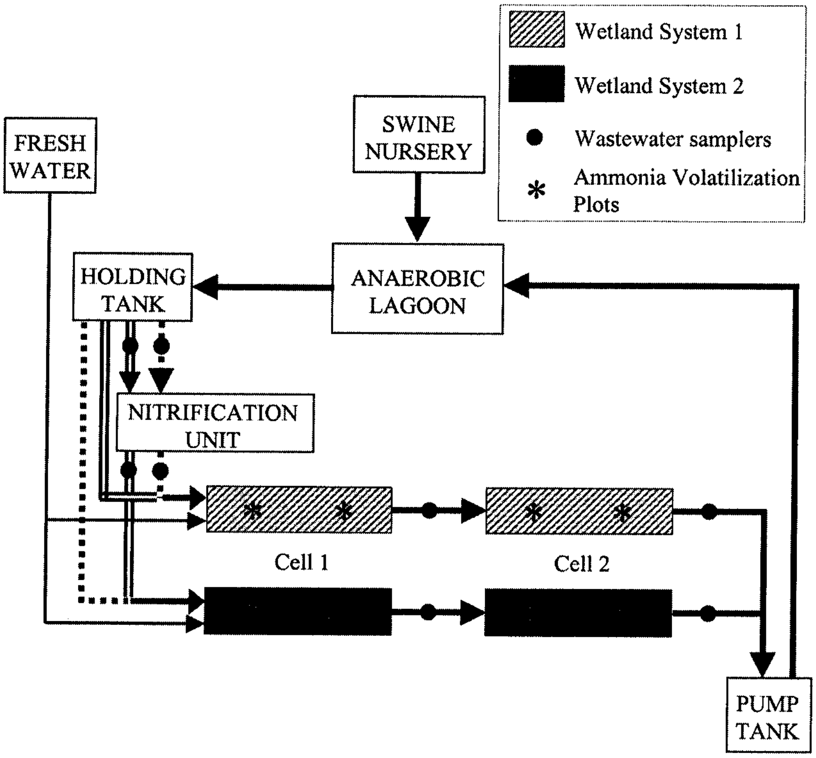

Fig. 1. Schematic of the constructed wetland design showing sampling and plot locations. Dashed lines indicate the flow scheme of swine wastewater from September 2000 through April 2001. Double lines indicate the flow scheme of swine wastewater from July through November 2001.

tank contained 130 l of polyethylene glycol nitrifying pellets of 3–4 mm size (Hitachi Plant Engineering & Construction Co., Tokyo; note: mention of trade name, proprietary product, or vendor is for information only and does not constitute a guarantee or warranty of the product by US Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that may also be suitable). Vanotti et al. (1999) describes the design and function of the nitrification unit.

Nitrate-nitrogen averaged 40 and 42% of the total nitrogen in the nitrified wastewater applied to Wetland System 1 and 2, respectively. The flow rate and the size of the nitrification unit ensured that the wastewater was only partially nitrified. The chosen flow rate produced a hydraulic residence time lower than that necessary for full nitrification (Vanotti and Hunt, 2000). Except in cold weather, wastewater flow to the unit was 1.3 l min^{-1}. Flow was reduced during cold weather to ensure partial nitrification of the wastewater. Consequently, the nitrogen load to Wetland System 1 was less than 20 kg nitrogen ha^{-1} per day from November 2000 through April 2001.

Fresh water was also applied at the head of the wetlands (Fig. 1). Freshwater was added to maintain a total hydraulic load of 17 mm per day, which ensured sufficient outflow from each system during warmer months of the year. Because of freshwater addition, wastewater nitrogen concentrations added to each system were diluted by approximately 65%. This level of freshwater addition might not be necessary in practical application because outflow from the wetlands is not necessary, but the addition of freshwater may be needed to reduce the ammonia concentration of wastewater below levels toxic to the wetland plants. Fresh water contributed negligible amounts of nitrogen. Effluent from each wetland system was returned to the lagoon.

Inflows to the first and second cells of each wetland system were measured using tipping buckets equipped with reed switches and electronic counters. Outflows from the second cells were measured with V-notch weirs where water height was measured by pressure transducers (Druck, Inc., PDCR 950, New Fairfield, CT). Fresh water inflows were measured with inline flowmeters (Neptune T-10). Tipping bucket, flowmeter, and pressure transducer readings were recorded continually with a datalogger (Campbell Scientific, Inc., CR23, Logan, UT).

Wastewater was collected from the outlets of the holding tank and the nitrification unit every 21 h and compiled into semiweekly (3.5 day) composite samples using a refrigerated sampler (American Sigma, Sigma 900 MAX, Loveland, CO). At the remaining sampling locations (Fig. 1), wastewater was collected every 8 h and compiled into semiweekly composite samples using automated samplers (ISCO 3700, Lincoln, NE). The ISCO samplers collected two sets of samples, one set with sulfuric acid added as a preservative and one without acid. Composite samples were collected weekly and refrigerated until analyzed.

To assess the progression of nitrogen removal as wastewater flowed through the wetland systems, duplicate samples of wastewater were manually collected along transects in Wetland System 1 and 2 during 1 day in October 2000 and August 2001, respectively. Along the length of each wetland system, samples were collected in 0.6-m increments from the inlet to a distance of 3 m and, thereafter, in 4-m increments measured from the inlet to the outlet. These samples were acidified with sulfuric acid and refrigerated until analyzed.

Ammonia volatilization was measured at two locations in each wetland cell (total of eight locations) in October 2000 and in August 2001 (Fig. 1). Poach et al. (2002) give a detailed description of the method used to measure ammonia volatilization. To describe briefly, an open-ended enclosure with forced airflow was used to measure ammonia volatilization (Fig. 2). At the beginning of a test, gas-washing bottles were mounted at the inlet and outlet of the enclosure and attached to vacuum pumps. The gas-washing bottles contained 80-ml of 0.1 N sulfuric acid each to collect samples of ammonia entering and leaving the enclosure. The sides of the enclosure were then dropped and locked into place. Two variable-speed fans mounted at each end of the enclosure were turned on and adjusted to equilibrate pressure inside the enclosure. Vacuum pumps were then turned on to begin ammonia sampling. The duration of each test was 2 h. During each test, environmental conditions in the enclosure were collected and recorded (Table 1). Grab samples and pH readings of wastewater were collected from an area contiguous to the study location during each test.

2.4. Data analysis

Using EPA methods, wastewater samples were analyzed for ammoniacal nitrogen (351.2), nitrate-nitrogen (353.1), and TKN (351.2; Kopp and McKee, 1983). Analyses were performed with a TrAAcs 800 Auto-Analyzer (Bran+Luebbe, Buffalo Grove, IL) or a Technicon AAII analyzer (Technicon Instruments Corp., Tarrytown, NY). For samples collected by the ISCO samplers, ammoniacal nitrogen and nitrate-nitrogen were determined on the acidified samples, and TKN was determined on the non-acidified samples. Total nitrogen was the sum of TKN and nitrate-nitrogen.

Semiweekly wastewater flows and nitrogen concentrations were then used to determine the semiweekly nitrogen loads at the inlets and outlets of the wetlands using the following equation:

$$L = [(C/10^6) \times F]/Aw \quad (2)$$

where, L, semiweekly nitrogen load (kg ha^{-1} per day); C, semiweekly nutrient concentration (mg l^{-1}); F, semiweekly wastewater flow (l per day); and Aw, wetland area (ha).

Monthly means of nitrogen load were used to determine the efficiency of nitrogen removal by each system using the following equation:

$$\mathrm{Eff}_m = [(MLi - MLo)/MLi] \times 100 \quad (3)$$

where, Eff$_m$, monthly efficiency of nitrogen re-

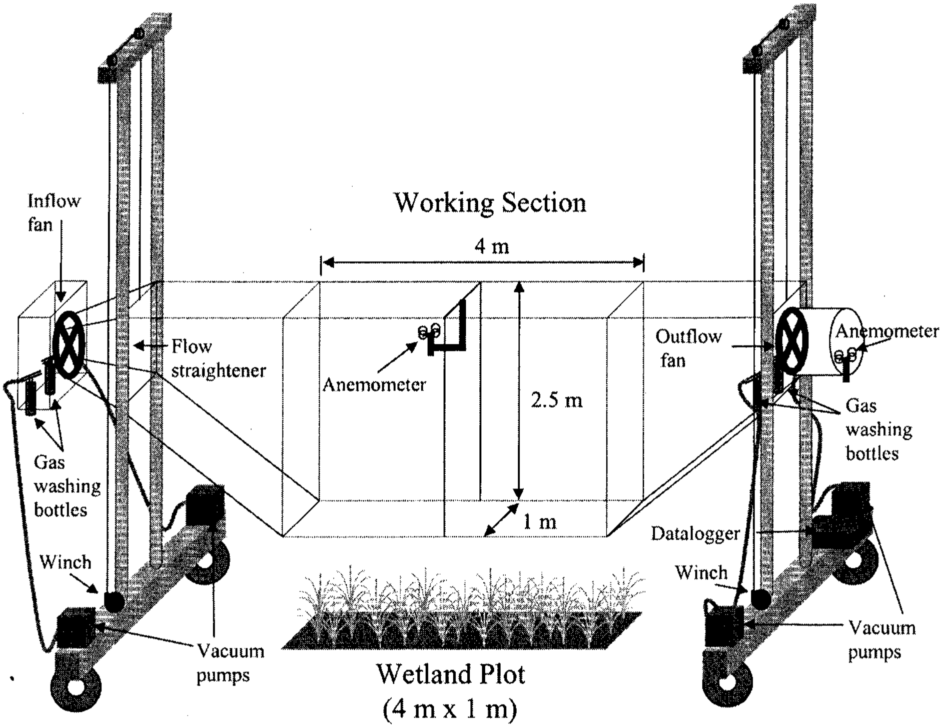

Fig. 2. Diagram of enclosure used to measure ammonia volatilization showing dimensions and component placement.

moval (%); Mli, monthly mean inlet nitrogen load (kg ha^{-1} per day); and Mlo, monthly mean outlet nitrogen load (kg ha^{-1} per day).

Gas-wash-bottle samples were treated as if they were digested samples and were analyzed for ammonia-nitrogen with a TrAAcs 800 Auto-Analyzer (Bran+Luebbe, Buffalo Grove, IL) using EPA method 351.2 (Kopp and McKee, 1983). Hourly rates of ammonia-nitrogen volatilization in mg nitrogen m^{-2} h^{-1} were determined using the following equation:

$$\mathrm{Va} = [\mathrm{dA} \times \mathrm{Fd}/\mathrm{Ap}/\mathrm{D}] \times [1\ \mathrm{mg}/1000\ \mu\mathrm{g}] \quad (1)$$

where, Va, ammonia-nitrogen volatilization; dA, difference in ammonia-nitrogen captured at the enclosure outlet and inlet in μg; Fd, Air flow through enclosure in l min^{-1} divided by the air sampling rate of 6 l min^{-1}; Ap, Plot area of 4 m^2; and D, duration of the test in hours.

2.5. *Statistical analysis*

Monthly means of nitrogen removal efficiency were used to test for a significant treatment effect. February, March, and April data were excluded from the analysis to insure a balanced design. The statistical test was performed as a 2 × 2 latin square design with sub-sampling using the ANOVA procedure of the SAS system (SAS, 1990). As a consequence of the 2 × 2 latin square design, the error for main effects had zero degrees of freedom. Thus, the mean square error for the month by wetland system factor was used as an estimate for the main effects error.

For each ammonia volatilization test, a significant difference between mean ammonia-nitrogen captured by inlet and outlet bottles was determined using a studentized *t*-test. Individual *t*-tests were made more powerful by pooling standard deviations for all tests to estimate the sampling variance.

Table 1
Parameters for ammonia volatilization tests conducted in October 2000 and August 2001 on two constructed wetland systems in Duplin County, NC, that received partially nitrified and unaltered swine wastewater

Wetland system	Wastewater treatment	Wetland cell-plot	Plot air		Plot manure				
			Speed[a] (m s^{-1})	Temperature (°C)	Temperature (°C)	pH	$NH_{3/4}$-N[b] (mg l^{-1})	NH_3-N[c] (%)	NH_3-N[d] (mg l^{-1})
October-00									
1	Partially Nitrified	1-1	1.0	28.4	22.3	7.8	39	2.6	1.0
		1-2	1.8	23.6	21.1	7.7	34	2.0	0.7
		2-1	0.6	26.4	19.0	7.2	18	0.6	0.1
		2-2	1.3	30.8	23.4	7.3	7	1.0	0.1
2	Unaltered	1-1	0.3	23.5	18.2	7.0	63	0.3	0.2
		1-2	1.5	30.9	24.9	7.2	60	0.8	0.5
		2-1	0.6	27.4	18.8	7.6	73	1.3	0.9
		2-2	1.9	31.7	22.4	7.4	67	1.2	0.8
August-01									
1	Unaltered	1-1	1.4	32.5	25.0	6.9	72	0.5	0.3
		1-2	0.9	31.6	ND[e]	6.9	52	ND	ND
		2-1	1.5	26.6	22.7	7.0	58	0.5	0.3
		2-2	0.8	32.4	23.4	6.9	32	0.4	0.1
2	Partially Nitrified	1-1	0.9	35.6	27.1	7.1	44	0.8	0.4
		1-2	1.0	32.8	25.8	7.0	38	0.5	0.2
		2-1	0.8	26.6	22.6	7.0	64	0.4	0.3
		2-2	0.3	35.6	23.1	6.8	52	0.3	0.2

[a] Airspeed measured by an anemometer located at the center of the enclosure, 2 m above the plot surface.

[b] Ammoniacal nitrogen ($NH_{3/4}$-N) concentration.

[c] Percent of ammoniacal nitrogen present as aqueous ammonia (NH_3-N) and determined as follows: $NH_3\text{-N} = 10\ \text{pH}/([6344/(273+\text{manure temperature})]+10\ \text{pH}) \times 100$ (modified Eq. (1) from Vanotti and Hunt, 2000).

[d] Concentration of aqueous ammonia-nitrogen (NH_3-N).

[e] ND, not determined.

Prior research on ammonia volatilization from manure storage lagoons indicated that ammonia volatilization was affected by manure ammoniacal nitrogen concentration, manure temperature, manure pH, and wind speed (Harper et al., 2000). The effect on ammonia volatilization of these variables along with the mass of ammonia entering the enclosure were investigated with the regression procedure of the SAS system (SAS, 1990).

3. Results and discussion

3.1. Nitrogen removal

Partial nitrification of swine wastewater increased the efficiency of total nitrogen removal by both wetland systems with the greater treatment difference occurring within the first cell ($P < 0.003$; Table 2). Under both treatments, the wetlands had similar hydraulic residence times and total nitrogen loading rates. The improved removal efficiency for total nitrogen resulted from the removal of applied nitrate-nitrogen because partial nitrification did not appear to affect the amount of TKN removed by the wetland systems. Partial nitrification did appear to improve the efficiency of ammoniacal nitrogen by the first cell, but this is misleading because it was likely a result of the differences in the ammoniacal nitrogen loads between wastewater treatments.

Transect samples indicated that both wetland systems had the ability to remove most all of the applied nitrate-nitrogen within 4 m from the inlet (Fig. 3). These results indicate that partial nitrification of the wastewater prior to wetland application improved total nitrogen removal because it increased nitrate available for wetland denitrification. This was expected because denitrification in these systems was found to be nitrate limited (Hunt et al., 2002a). The removal of nitrate-nitrogen in the first 4 m (14.4 m^2) of a wetland would require denitrification rates of 188 and 100 kg N ha^{-1} per day for Wetland System 1 and 2, respectively, assuming denitrification was solely responsible for nitrate removal. Denitrification enzyme analysis of the wetland soils, which included a floating detritus/sludge layer, indicated that they have the potential to exhibit such denitrification rates with nitrate additions (Hunt, et al., 2002b).

Nitrate-nitrogen was measured in outlet samples even though transect samples indicated that the wetlands were very effective at removing the applied nitrate (Table 2). Nitrate-nitrogen measured at the outlets was most likely nitrate-nitrogen produced in the wetland instead of nitrate-nitrogen applied at the inlet. The fact that nitrate-nitrogen was measured at the outlets during the periods when unaltered wastewater was applied to the wetlands supports this supposition. Also, transect samples indicated that all of the applied nitrate-nitrogen was removed before the outlet of the first cell (Fig. 3). It is possible that the wetlands were unable to denitrify nitrate-nitrogen produced close to the outlets of each wetland cell. Denitrification enzyme analysis indicates that denitrification decreases as water levels increase (Hunt et al., 2003), and water levels are highest at the outlets of each wetland cell. It is also possible that some ammoniacal nitrogen was converted to nitrate in the sampling wells and not in the wetland. Therefore, the presence of nitrate-nitrogen in outlet samples may not be indicative of wetland function.

When nitrate is readily available, carbon availability can become the limiting factor for denitrification (Focht and Verstraete, 1977; Hunt et al., 1999). Carbon in the swine wastewater and accumulated in the wetlands, which received swine wastewater for 7 years prior to this experiment, was sufficient to support the observed nitrate removal. Because this experiment contained these carbon sources, caution should be exercised in applying these results to other systems, especially when wastewater with low carbon is applied to newly constructed systems. In such cases, additional carbon could be supplied by adding raw manure, straw, or methanol to the wetland.

The full area of Wetland System 1 was significantly more effective ($P < 0.002$) at removing total nitrogen from both types of wastewater than Wetland System 2 even though their first cells were similarly effective (Table 3). Difference in the total nitrogen removal efficiency of each system resulted from significant differences in their ability

Table 2
Operational parameters and nitrogen removal efficiencies averaged across wetland systems for partially nitrified and unaltered swine wastewater treatment by the first cell and the full area of constructed wetlands in Duplin County, NC, USA, as determined over two 5-month periods

Wetland section	Wastewater treatment	Flow (l per day)		HRT^{b} (days)	Total nitrogen					Nitrate/nitrite nitrogen				
		In^{a}	Out		Concentration (mg l^{-1})		Load (kg ha^{-1} per day)		Mass Removal^{b} (%)	Concentration (mg l^{-1})		Load (kg ha^{-1} per day)		Mass removal^{b} (%)
					In	Out	In	Out		In	Out	In	Out	
First cell	Partially nitrified	1447	3088	6 (3)^{a}	298	56	36	14	64 (10)^{a}	116	7	14	2	86 (8)
	Unaltered	1248	3141	5 (1)^{a}	335	93	35	23	32 (12)^{b}	2	3	0	1	-
Total System	Partially nitrified	1447	3357	12 (5)^{a}	298	33	18	4	78 (14)^{a}	116	4	7	1	88 (15)
	Unaltered	1248	3177	11 (1)^{a}	335	42	17	5	68 (22)^{b}	2	7	0	1	-
					Total Kjeldahl nitrogen					Ammoniacal nitrogen				
					Concentration (mg l^{-1})		Load (kg ha^{-1} per day)		Mass removal^{b} (%)	Concentration (mg l^{-1})		Load (kg ha^{-1} per day)		Mass removal^{b} (%)
					In	Out	In	Out		In	Out	In	Out	
First cell	Partially nitrified				184	49	22	12	50 (18)^{a}	141	38	17	9	48 (17)^{a}
	Unaltered				338	89	35	22	35 (13)^{a}	265	80	27	20	27 (15)^{b}
Total system	Partially nitrified				184	29	11	4	71 (24)^{a}	141	22	8	3	73 (26)^{a}
	Unaltered				338	34	17	4	73 (21)^{a}	265	29	14	4	71 (26)^{a}

[a] Wastewater flow only. Freshwater inflow was 2492 and 2378 l per day for nitrified and unaltered wastewater, respectively.

[b] Mean (±S.D.) of hydraulic residence time (HRT) and of mass removal for each nitrogen form are compared within a wetland section. Different letters indicate a statistically significant difference (alpha = 0.05).

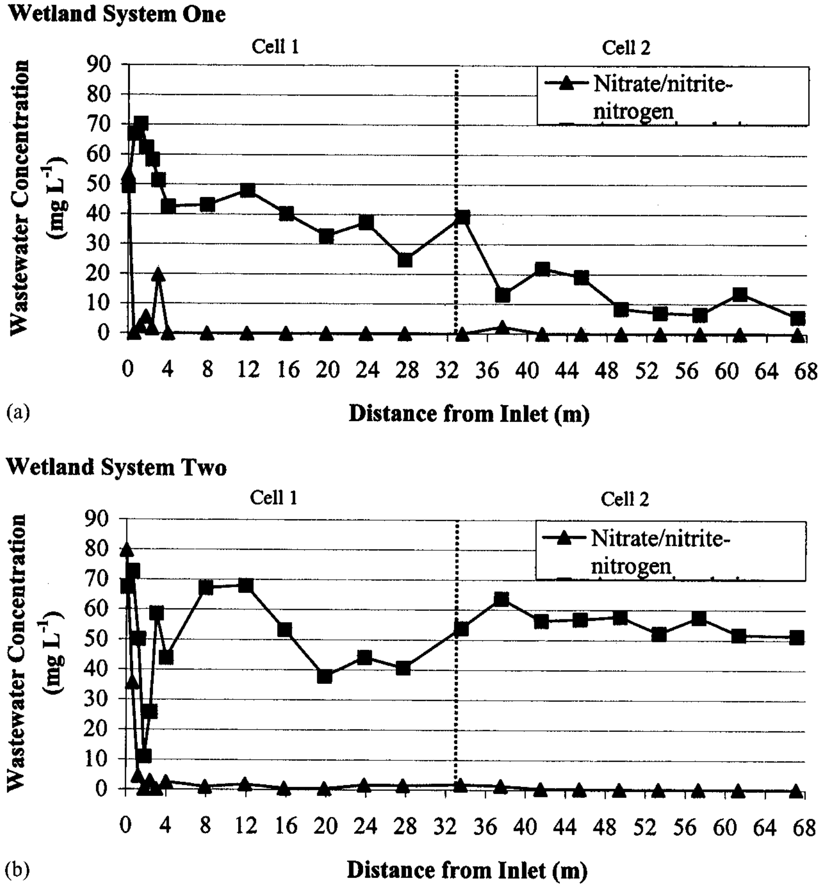

Fig. 3. Concentration of ammoniacal nitrogen and nitrate/nitrite-nitrogen in swine wastewater collected along a transect from the inlet to the outlet of two constructed wetland systems.

to remove TKN ($P < 0.003$) and ammoniacal nitrogen ($P < 0.003$). Ammoniacal nitrogen was more effectively removed by the full area of Wetland System 1 compared with Wetland System 2 (Table 3).

At our nitrogen application rates, nitrification/denitrification is considered to be the dominant ammoniacal nitrogen removal mechanism for these systems (Hunt et al., 2002a; Poach et al., 2002). The fact that both systems were effective at removing nitrate leads to the conclusion that Wetland System 1 removed more ammoniacal nitrogen because it supported more nitrification. Hunt et al. (2002a) also surmised that Wetland System 1 supported more nitrification than Wetland System 2. Their experiment was conducted prior to the plant community changes exhibited by Wetland System 2. The enhanced nitrification of Wetland System 1 indicates that either it's plants were better at oxygenating the soil and at supporting nitrifiers or that it had a higher plant density compared with Wetland System 2 or both. Nonetheless, more research should be performed before definitively concluding that a *Schoenoplectus* sp. dominated system is superior for nitrogen removal from animal wastewater.

3.2. Ammonia volatilization

Partial nitrification of swine wastewater decreased but did not totally eliminate ammonia volatilization from the two constructed, wetland

Table 3

Operational parameters and nitrogen removal efficiencies averaged across wastewater treatments for the first cell and full area of two wetland systems in Duplin County, NC, USA, that received partially nitrified and unaltered swine wastewater over two 5-month periods

Wetland section	Wetland system	Flow (l per day)		HRT[b] (days)	Total nitrogen					Nitrate/nitrite nitrogen				
		In[a]	Out		Concentration (mg l^{-1})		Load (kg ha^{-1} per day)		Mass removal[b] (%)	Concentration (mg l^{-1})		Load (kg ha^{-1} per day)		Mass removal[b] (%)
					In	Out	In	Out		In	Out	In	Out	
First cell	1	1265	2850	6 (3)[a]	313	70	33	16	53 (22)[a]	49	6	5	1	83 (9)[a]
	2	1428	3285	5 (1)[a]	320	79	38	20	44 (16)[a]	68	5	9	1	88 (7)[a]
Total system	1	1265	2944	12 (4)[a]	313	19	16	2	85 (11)[a]	49	6	3	1	80 (18)[a]
	2	1428	3207	10 (2)[a]	320	56	19	7	61 (16)[b]	68	5	5	1	97 (1)[a]
					Total Kjeldahl nitrogen					Ammoniacal nitrogen				
					Concentration (mg l^{-1})		Load (kg ha^{-1} per day)		Mass removal[b] (%)	Concentration (mg l^{-1})		Load (kg ha^{-1} per day)		Mass removal[b] (%)
					In	Out	In	Out		In	Out	In	Out	
First cell	1				269	65	27	15	50 (20)[a]	205	57	21	13	44 (21)[a]
	2				254	74	29	19	35 (9)[a]	201	61	23	16	32 (15)[a]
Total system	1				269	12	14	2	89 (9)[a]	205	8	11	1	91 (10)[a]
	2				254	51	15	6	55 (18)[b]	201	43	12	5	52 (19)[b]

[a] Wastewater flow only. Freshwater inflow was 2352 and 2518 l per day for Wetland System 1 and 2, respectively.

[b] Mean (±S.D.) of hydraulic residence time (HRT) and of mass removal for each nitrogen form are compared within a wetland section. Different letters indicate a statistically significant difference (alpha = 0.05).

systems. When the wetlands received partially nitrified wastewater, only one of eight tests showed significant evidence ($P < 0.1$) of ammonia volatilization (2.1 mg nitrogen m^{-2} h^{-1}; Table 4). Whereas, when the wetlands received unaltered wastewater, six of the eight tests showed significant evidence of ammonia volatilization (3.8–10.9 mg nitrogen m^{-2} h^{-1}). One test exhibited a significant negative value, which indicates that the wetland absorbed rather than emitted ammonia. This test had the highest background concentration of ammonia as exhibited by the inlet bottles. Absorption probably occurred because the background ammonia in the atmosphere was higher than the ammonia compensation point of the plot.

A rate of 2.1 mg nitrogen m^{-2} h^{-1} for ammonia-nitrogen volatilization translates to 0.5 kg nitrogen ha^{-1} per day. This was approximately 3% of the total nitrogen loaded to and 4% of the total nitrogen removed by the wetlands when they received partially nitrified wastewater. The average volatilization for the wetland systems was actually lower than 0.5 kg nitrogen ha^{-1} per day when they received partially nitrified wastewater because the other plots exhibited rates that were below 2.1 mg nitrogen m^{-2} h^{-1}. Therefore, ammonia volatilization was inconsequential to the total nitrogen budget of the wetlands when they received partially nitrified wastewater.

Regression analysis revealed that the ammoniacal nitrogen concentration of the plot wastewater and the wind speed across the plot were significant variables ($P < 0.025$) that explained 55% of the variation in the ammonia-nitrogen volatilization. The ammoniacal nitrogen concentration of the plot wastewater was positively correlated with and explained 33% of the variation in ammonia-nitrogen volatilization (Fig. 4). Other variables in Table 1 were not found to have significant relationships with ammonia-nitrogen volatilization.

The impact of ammoniacal nitrogen concentration on ammonia volatilization is also seen when

Table 4
Ammonia-nitrogen (NH_3-N) volatilization from two constructed wetland systems in Duplin County, NC, that received unaltered and partially nitrified wastewater as determined by the difference in ammonia captured at the inlet and outlet of a steady-state enclosure

Wetland system	Wastewater treatment	Wetland cell-plot	Air flow (l min^{-1})	NH_3-N (μg)			NH_3-N volatilization[a] (mg m^{-2} h^{-1})
				In	Out	Out–In	
October-00							
1	Partially Nitrified	1-1	26203	4.8	5.7	0.8	0.5
		1-2	42320	3.4	4.5	1.2	1.0
		2-1	41752	9.5	9.7	0.2	0.2
		2-2	54381	5.6	7.5	1.8	2.1
2	Unaltered	1-1	35125	8.6	14.7	6.1**	4.5
		1-2	41123	5.2	10.0	4.8**	4.1
		2-1	22357	4.0	13.2	9.1**	4.3
		2-2	46653	2.2	13.4	11.2**	10.9
August-01							
1	Unaltered	1-1	43690	6.1	15.4	9.4**	8.5
		1-2	27129	5.8	8.5	2.6	1.5
		2-1	39865	11.0	15.6	4.5**	3.8
		2-2	28766	13.3	9.3	−3.9**	−2.4
2	Partially Nitrified	1-1	19772	9.0	10.1	1.1	0.4
		1-2	23920	10.1	14.2	4.2**	2.1
		2-1	29095	12.0	10.5	−1.5	−0.9
		2-2	20593	5.6	7.2	1.7	0.7

**, Statistically different from zero ($LSD_{0.1}$ for Out–In = 3.4 μg).

[a] Volatilization = [(NH_3-N out − NH_3-N in) × (enclosure airflow/6 l min^{-1})/4 m^2/2 h] × (1 mg/1000 μg).

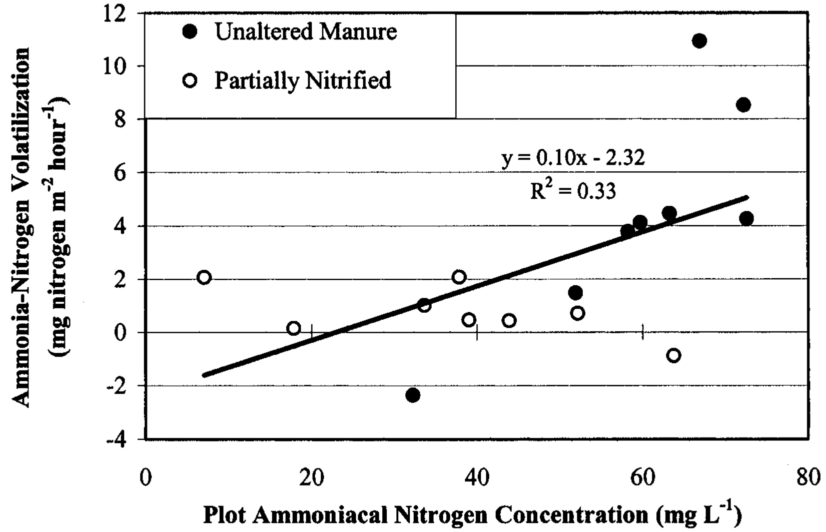

Fig. 4. Regression of ammonia-nitrogen volatilization from constructed wetlands vs. the ammoniacal nitrogen concentration of the wastewater in the test plots.

one considers the ammonia volatilization results reported by Poach et al. (2002) for the same wetland systems when they received unaltered swine wastewater. Ammonia-nitrogen concentration of wastewater was positively correlated ($P < 0.0004$) with and explained 64% of the variation in ammonia-nitrogen volatilization when the data from Poach et al. (2002) was combined with the data from this study (Fig. 5). Therefore, ammonia-nitrogen volatilization measured in this study was lower than that measured by Poach et al. (2002) because of differences in the ammoniacal nitrogen concentration of the wastewater applied to the wetlands.

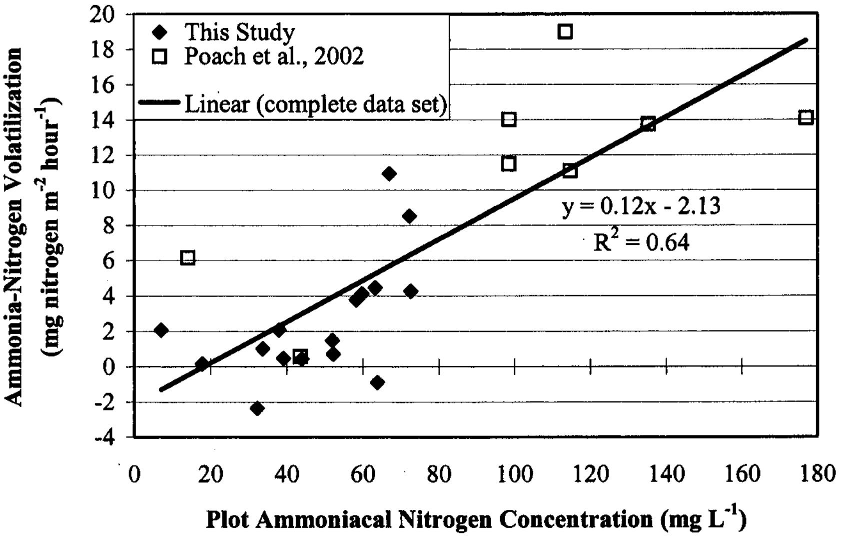

Fig. 5. Regression of ammonia-nitrogen volatilization from constructed wetlands vs. the ammoniacal nitrogen concentration of the wastewater in the test plots (data from Poach et al., 2002 included).

The relationship between ammoniacal-nitrogen concentration and ammonia-nitrogen volatilization supports the straightforward contention that ammonia volatilization was lower when the wetlands received partially nitrified wastewater because the nitrification process lowered the ammoniacal nitrogen concentrations in the wastewater applied to the wetlands. This relationship also indicates that ammonia volatilization could be reduced by diluting liquid swine manure with water, but that would incur the disadvantage of increasing the total volume of wastewater that needed treatment. Therefore, nitrification of swine wastewater should be the preferred method for the reduction of ammonia volatilization.

4. Conclusions

Partial nitrification of swine wastewater prior to wetland application improved the treatment performance of our constructed wetlands by both enhancing total nitrogen removal and reducing ammonia volatilization. Total nitrogen removal by the constructed wetlands was improved as a result of nitrate removal, which indicates that partial nitrification enhanced denitrification. Both wetland systems exhibited the ability to remove nitrate-nitrogen in the first 14.4 m^2. Partial nitrification also reduced ammonia volatilization to levels that were inconsequential to the total nitrogen budget of the wetlands. Ammonia volatilization was reduced because partial nitrification lowered the ammoniacal nitrogen concentration of the wastewater.

While both systems effectively removed nitrate-nitrogen from partially nitrified swine wastewater, the total nitrogen removal from the wastewater was still limited by their ability to convert the remaining ammoniacal nitrogen to nitrate. Wetland System 1 was significantly more effective at removing total nitrogen than Wetland System 2, regardless of the type of wastewater treatment, because it was likely better able to convert ammoniacal nitrogen to nitrate.

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