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SEASONAL DYNAMICS OF NUTRIENTS AND PHYSICO-CHEMICAL CONDITIONS IN A CONSTRUCTED WETLAND FOR SWINE WASTEWATER TREATMENT

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Summary:

Seasonal changes in nutrient concentrations and physico-chemical conditions were monitored in six, 4- × 30-m, constructed wetland cells. Wetland cells were planted to rushes, bulrushes, bur-reed, cattails, rice or soybeans. Swine wastewater N-loadings were 3 kg ha^{-1} day^{-1}. Total mass removal for soluble inorganic forms of N and P was 90 and 80%, respectively; however, the removal efficiencies were low during a cooler period (Oct.-Mar.). Redox potentials were highly reducing (+100 to -250 mV) during warm periods and more oxidative (up to +450 mV in rush/bulrush cells) during the cooler period. An oxidative component may be desirable for sustainable efficiency of the system.

Keywords:

Nitrogen, Phosphorus, Reduction, Oxidation, Nitrification

INTRODUCTION

Swine production is an important agricultural enterprise in the Eastern Coastal Plain (ECP) that requires significant attention to waste management. The disposal of swine waste is of much concern because of its liquid nature and high plant nutrient concentration (C, N, and P). Disposal of wastewater can be a difficult problem for swine producers who have limited area for land application near their swine operations and because of the elevated cost of transporting or pumping liquid manures. Therefore, wastewater disposal must be accomplished in a reliable and sustainable manner to avoid significant environmental deterioration of shallow groundwaters, lakes, wetlands, and nutrient-sensitive streams of the ECP environment (Duda, 1982; Evans et al., 1984; Hubbard and Sheridan, 1989; Stone et al., 1989; 1992). As an alternative to land application, constructed wetlands have received considerable attention as a method of wastewater treatment that could reduce the land requirements (Hammer, 1989; Reed, 1993). However, questions exist about the long-term efficiency of constructed wetlands for swine wastewater treatment; specifically, questions exist about loading rates, oxidative/reductive conditions, denitrification potential, phosphorus removal efficiency, and ammonia toxicity to wetland plants.

This study was undertaken to investigate the capacity of surface flow constructed wetlands, planted to natural wetland or water-tolerant agronomic plants, to treat swine wastewater. The objective of this report is to evaluate seasonal changes on water solution chemistry and physico-chemical conditions in a constructed wetland containing three different plant communities.

MATERIALS AND METHODS[1]

Wetland Cells

Six, 4- x 30-m, wetland cells were constructed in Duplin Co., NC, in 1992. They were divided into three parallel sets of two end-on-end cells (Hunt et al., 1994). The cell bottoms and sidewalls were lined with clay, which was covered with 20 to 30 cm of loamy sand soil. Slopes were 0.2% or less, and water depth at the end of the slope was maintained below 15 cm.

Plant Materials

Four cells were planted to natural wetland vegetation in 1992. One set of two cells (1 and 2, end-on-end) contained rush (*Juncus effusus*) and bulrushes (*Scirpus americanus*, *Scirpus cyperinus*, and *Scirpus validus*), and another set of two cells (3 and 4) contained bur-reed (*Sparganium americanum*) and cattails (*Typha angustifolia* and *Typha latifolia*). Estimates of

[1] Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Dept. of Agr. and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

dry-plant biomass were obtained monthly from three randomly collected 0.25-m^2 samples. The third set of two cells contained agronomic crops. Cell 5 contained soybean (*Glycine max*) grown in saturated-soil culture on 1-m-wide beds that were surrounded by ditches of approximately 10-cm depth (Cooper et al., 1992; Nathanson et al., 1984). Water level in the ditches was held at about 5 cm below the surface. Group V (cvs. Essex, Holladay, and Hutcheson) and group VI (cvs. Brim, Centennial, and Young) soybean cultivars were planted in 18-cm-wide rows in a randomized complete block design with four replications. Cell 6 contained flooded rice (*Oryza sativa* cv. Maybelle). Both agronomic crops were planted in May 1993, and plant densities were 750,000 plants ha^{-1} in both cases.

Monitoring Equipment

Six V-notch weirs and six PDS-350 ultrasonic open-channel flowmeters (Control Electronics, Morgantown, PA) were installed at the inlet and outlet of each set of cells. Seven ISCO 3700 samplers (ISCO, Lincoln, NE) were installed; one sampler collected samples of the wastewater inflow, and the other six sampled the water at the end of each single cell. A CR7X data logger with three multiplexers (Campbell Scientific, Logan, UT) were installed for hourly acquisition of flow, weather parameters, and soil redox potential data. The water sampler combined hourly samples into composites.

Water Analysis

Water samples were analyzed for electrical conductivity (EC) and pH by electrometric methods. Nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), and orthophosphate-phosphorus (*o*-PO_4-P) were analyzed in accordance with the USEPA recommended methodology (Kopp and McKee, 1983). Nitrogen and phosphorus analyses were accomplished by use of a TRAACS 800 Auto-Analyzer. Total organic carbon (TOC) and dissolved organic carbon (DOC) was analyzed with a Dhorman DC-190 carbon analyzer.

Soil Redox Potential

Soil redox potential was monitored continuously at 2-, 5-, and 10-cm depths with a total of ninety Platinum electrodes arranged in three clusters of five electrodes per cell with one Ag/AgCl reference electrode per cluster. Platinum electrodes were constructed according to Faulkner et al. (1989) and tested in a pH-buffered quinhydrone solution. Redox potential readings were taken every five minutes, averaged every hour, and stored in the CR7X data logger. Redox readings were adjusted to the standard hydrogen electrode (Eh) by adding 200 mV. Soil pH was measured periodically on wet soil samples to eventually adjust redox potentials to pH 7.

Nutrient Loads

The continuous flow loading was automated with float control valves in a mixing tank, which provided automated loading of the desired proportion of lagoon liquid and dilution water. In order to prevent the potential of damage to wetland plants, it was desirable to start wastewater application to the cells with low NH_3-N loading rates. Therefore, wastewater (Table 1) was diluted ≥ 10 fold with fresh water and applied at a N rate of 3 kg ha^{-1} day^{-1}. This relatively low daily N application rate required a high dilution in order to maintain the hydraulic conditions of a wetland (i.e., wastewater with 25 mg L^{-1} N provides 3 kg ha^{-1} day^{-1} of N with a loading depth of only 12 mm day^{-1}). Since 6-mm hydraulic loading would not meet evapotranspiration demands during the summer months, the dilution and hydraulic loading were increased as needed to maintain the wetland and the 3 kg ha^{-1} day^{-1} N application rate. Thus, the nitrogen concentration in the inflow wastewater was lower for the summer period.

Table 1. Characteristics of non-diluted wastewater from the anaerobic lagoon (Hunt et al., 1994).

Parameters	Units	Mean	Std. Dev.
pH		7.53	0.14
Total Solids	g kg^{-1}	1.86	0.47
Volatile Solids	g kg^{-1}	0.73	0.32
Total Organic Carbon	mg L^{-1}	235	124
Chemical Oxygen Demand	mg L^{-1}	737	237
Biochemical Oxygen Demand	mg L^{-1}	287	92
Total Kjeldahl Nitrogen	mg L^{-1}	365	41
Ammonia-Nitrogen	mg L^{-1}	347	52
Nitrate-Nitrogen	mg L^{-1}	0.04	0.03
Total Phosphorus	mg L^{-1}	93	11
Othophosphate-Phosphorus	mg L^{-1}	80	9

Nutrient Balances

Mass balances were calculated for C, N, and P using flowmeter and nutrient concentration data. The mass balance was used to estimate the specific reduction as mass reduction of nutrient per cell area per day (g m^{-2} d^{-1}). The mass removal or treatment efficiency was expressed as percentage of mass reduction of a nutrient in the effluent with respect to the nutrient mass inflow.

RESULTS AND DISCUSSION

Mean above-ground dry matter productions estimated for rush/bulrushes in 1993 and 1994 were 21 and 12 Mg ha^{-1}, respectively, and for cattails/bur-reed were 9 and 33 Mg ha^{-1}, respectively. These above-ground biomass productions are similar to the ones reported for emergent aquatic macrophytes by DeBusk and Ryther (1987). Dead plant material altered the surface of the wetland cells by providing increased surface area for microbial processes, particularly nitrification. In the spring of 1994, growth of rush/bulrushes in cells 1 and 2 was restricted by the heavy mat of plant litter. However, plant growth was reestablished throughout the cells by the summer. The rice yield was 2.8 Mg ha^{-1}. Mean seed yields of groups V and VI soybean were 1.9 and 3.3 Mg ha^{-1}, respectively. Group VI soybean yields were much higher than the state average, and soybean cultivar Young yielded 3.8 Mg ha^{-1}.

Non-diluted wastewater characteristics are listed in Table 1. Total organic carbon, chemical oxygen demand (COD), and biological oxygen demand (BOD_5) are parameters that indicate the anaerobic conditions of the wastewater. Analyses of filtered and unfiltered samples of the diluted wastewater indicated that most TOC was in soluble form as DOC. According to Khalid et al. (1981), TOC is a more precise parameter than COD and BOD_5 to estimate the biochemical degradation potential of organic carbon (OC) present in wastewater effluents.

Quarterly means of DOC inflows ranged from 9 to 15 mg L^{-1}, and the mean outflows ranged from 7 to 32 mg L^{-1}. Wide temporal variations in DOC concentrations were observed. Higher values of DOC in the outflow indicate that at times the wetlands are a source of C due to accumulation and decomposition of dead plant materials. For this reason, the treatment efficiency was variable and particularly low (5 to 65 %) during the autumn and winter seasons (Oct. 1993 - Mar. 1994).

Nitrogen and phosphorus concentrations in non-diluted wastewater (Table 1) indicate that 95% of total Kjeldahl nitrogen (TKN) was in the soluble NH_3-N form, 86% of total phosphorus (TP) was in soluble form as *o*-PO_4-P, and NO_3-N concentrations were very low.

Mean NH_3-N concentrations in the diluted wastewater during the July-Sept. 1993 period decreased from 22 to 2 mg L^{-1} after treatment in the rush/bulrushes (cells 1 and 2) or bur-reed/cattails (cells 3 and 4), and they decreased to 0.3 mg L^{-1} after treatment in the soybean and rice cells (Table 2). The mass removal of NH_3-N by wetlands with all three vegetative communities was around 99% in this initial period. The substantial decrease was probably due to plant absorption and NH_3-N volatilization. However, some of the NH_3-N may have been nitrified, especially in the soybean and rice cells. The NH_3-N concentration in inflow wastewater was 49 mg L^{-1} during the Oct.-Dec. period when plant growth was dormant, but the rush/bulrushes and bur-reed/cattails cells still treated wastewater to mean outflow concentrations of 2 and 8 mg L^{-1}, respectively. This was likely a result of increased nitrification/denitrification. Ammonia-N discharge concentrations were lower in Jan.-Mar. and returned to 1 and 2 mg L^{-1} for the rush/bulrushes and bur-reed/cattails, respectively, in Apr.-June 1994.

Mean NO_3-N concentrations were low (< 2 mg L^{-1}) in the inflow wastewater during the entire study because of the anaerobic conditions in the lagoon (Table 3). Very little NO_3-N was accumulated in the treated wastewaters during the July-Sept. period; inflow and outflow mean concentrations were 0.8 and 0.1 mg L^{-1}, respectively. These low NO_3-N concentrations, along with the low redox conditions and the presence of NH_3-N in the outflow, suggest that very little nitrification occurred. However, in wetlands, nitrification

Table 2. Mean (X) and standard deviation (S) for ammonia-nitrogen of daily composite wastewater samples (1993-1994) from the wastewater inflow and outflow of every single cell.

Plants	Sampler		July-Sept.	Oct.-Dec.	Jan.-Mar.	Apr.-June
			---------mg L^{-1} ---------			
	Inflow	X	22	49	31	37
		S	11	23	6	10
J/S†	Cell 1	X	4	16	18	8
		S	4	13	16	7
	Cell 2	X	1	2	3	1
		S	2	2	5	2
S/T‡	Cell 3	X	4	22	15	2
		S	4	17	12	2
	Cell 4	X	1	8	5	2
		S	3	8	5	2
Soybean	Cell 5	X	13	--•	--	--
		S	7	--	--	--
Rice	Cell 6	X	0.3	--	--	--
		S	1	--	--	--

† J/S = *Juncus* sp. and *Scirpus* sp. (rush and bulrushes)
‡ S/T = *Sparganium* sp and *Typha* sp. (bur-reed and cattails)
• No data

and denitrification occur at the interface of aerobic and anaerobic zones, and nitrate could have been denitrified as rapidly as it was formed. More detailed measurements are needed before conclusions can be made about the extent of nitrate-N loss by denitrification. Nitrate-N was present in the outflow during Oct.-Dec. and Jan.-Mar. periods; quarterly mean values ranged from 2 to 10 mg L^{-1}. These values suggest that the decreased microbial respiration and increased O_2 solubility associated with the cooler weather allowed sufficient oxygen for increased nitrification or decreased NO_3-N removal from denitrification and plant uptake. During the Apr.-June 1994 period, discharge NO_3-N means were <0.5 mg L^{-1}.

Table 3. Mean ($\bar{X}$) and standard deviation (S) for nitrate-nitrogen of daily composite wastewater samples (1993-1994) from the wastewater inflow and outflow of every single cell.

Plants	Sampler		July-Sept.	Oct.-Dec.	Jan.-Mar.	Apr.-June
			----------	mg L^{-1}	----------	
	Inflow	$\bar{X}$	0.8	1	2	1
		S	0.4	0.4	0.6	0.9
J/S†	Cell 1	$\bar{X}$	0.4	9	6	8
		S	0.5	5	2	4
	Cell 2	$\bar{X}$	0.2	10	7	0.4
		S	0.3	7	6	1
S/T‡	Cell 3	$\bar{X}$	0.4	6	6	7
		S	0.5	4	3	5
	Cell 4	$\bar{X}$	0.2	5	2	0.1
		S	0.3	5	3	0.1
Soybean	Cell 5	$\bar{X}$	0.8	--*	--	--
		S	1.0	--	--	--
Rice	Cell 6	$\bar{X}$	0.1	--	--	--
		S	0.1	--	--	--

† J/S = *Juncus* sp. and *Scirpus* sp. (rush and bulrushes)
‡ S/T = *Sparganium* sp and *Typha* sp. (bur-reed and cattails)
* No data

This increased nitrification in the first cells during warmer period of 1994 may be due to the increased surface area associated with the plant litter from the first year's growth. Nitrification seems to be the limiting factor in nitrogen removal, and this view is supported by our preliminary denitrification enzyme assays. However, during the first year 90% of the applied nitrogen was removed by the wetlands. Table 4 shows the seasonal variation of the treatment efficiency. A high nitrogen removal efficiency for the rush/bulrushes (cells 1 and 2) and cattails/bur-reed (cells 3 and 4) was attained during the Jul.-Sept. period. The efficiency was lower (84 to 87%) during the autumn and winter seasons (Oct.-Dec. and Jan.-Mar.) with a recovery of the efficiency to almost 100% at the onset of warmer temperatures

Table 4. Mass removal efficiency of ammonia-nitrogen and nitrate-nitrogen* (1993-1994).

Plants	Cells	July-Sept.	Oct.-Dec.	Jan.-Mar.	Apr.-June
		%			
J/S†	1-2	98	86	87	99
S/T‡	2-3	98	84	86	99
S-R**	5-6	99	-	-	-

* Expressed as the combined mass removal efficiency (NH_4-N + NO_3-N)
† J/S = *Juncus sp.* and *Scirpus sp.* (rush and bulrushes)
‡ S/T = *Sparganium sp.* and *Typha sp.* (bur-reed and cattails)
** S-R = Soybean-Rice

by the end of March 1994. The soybean-rice treatment had a 99% removal efficiency during its growing period (July-Sept.).

Since phosphorus was present mostly as *o*-PO_4-P in the wastewater (Table 5), we believe that its effective removal was predominately by plant uptake, precipitation, and sorption to the soil substrate. Mass phosphorus removal by all wetlands was about 99% during the July-Sept. period. However, after this initial period, phosphate removal was not as good. Mean outflow values were > 2 mg L^{-1} for both the rush/bulrushes and bur-reed/cattails cells. Table 6 shows that the initial *o*-PO_4-P removal efficiency (July-Sept.) was similar for rush/bulrushes and cattails/bur-reed.

The efficiency declined from September 1993 to April 1994 (Table 6) probably because of low plant absorption and prevalent reduced soil conditions. The overall mass removal of *o*-PO_4-P during this first year was 80%. We think that a pre/post-wetland phosphorus precipitation and clarification step is desirable to improve its removal efficiency.

Average pH values of the wastewater and treated effluent varied from 6.5 to 8.4 units throughout the study without a seasonal pattern, probably due to dilution by rainfall. However, higher pH values may have occurred as a result of diurnal algal activity. High summer temperatures and basic pH values could have induced NH_3-N volatilization.

Average EC values for wastewater ranged from 260 to 1300 $\mu S \cdot cm^{-1}$. The EC of the applied wastewater was significantly lowered by flow through all of the wetland cells. Average EC values for treated effluent ranged from 150 to 980 $\mu S \cdot cm^{-1}$. The seasonal EC trends followed the seasonal and daily changes of soluble inorganic N (NH_3-N + NO_3-N) and *o*-PO_4 effluent concentrations in all cells.

Table 5. Mean (X̄) and standard deviation (S) for orthophosphate-phosphorus of daily composite wastewater samples (1993-1994) from the wastewater inflow and outflow of every single cell.

Plants	Sampler		July-Sept.	Oct.-Dec.	Jan.-Mar.	Apr.-June
			----------mg L^{-1} ----------			
	Inflow	X	6.0	12	6	6
		S	3.0	6	2	1
J/S†	Cell 1'	X	1.0	7	7	6
		S	0.8	4	4	1
	Cell 2	X	0.2	4	4	4
		S	0.3	3	2	1
S/T‡	Cell 3	X	0.5	7	7	3
		S	0.5	5	5	2
	Cell 4	X	0.1	3	3	2
		S	0.3	3	1	2
Soybean	Cell 5	X	2.0	--*	--	--
		S	0.6	--	--	--
Rice	Cell 6	X	0.2	--	--	--
		S	0.1	--	--	--

† J/S = *Juncus* sp. and *Scirpus* sp. (rush and bulrushes)
‡ S/T = *Sparganium* sp and *Typha* sp. (bur-reed and cattails)
* No data

Redox potential ranges (+100 to -250 mV) indicated strong reduced conditions in all wetland cells during July-Sept. The reduced conditions, lack of nitrification and denitrification, and high NH_3-N have been reported to be significant problems for treatment of municipal wastewater in constructed wetlands throughout the USA (Reed, 1993). Redox values in the Oct.-Dec. and Jan.-Mar. time periods were more oxidative than the summer values (some depths > +500 mV). The rush/bulrushes were more oxidized than the cattails/bur-reed, and there was diurnal as well as seasonal cycling of Eh. Cattails/bur-reed cells attained oxidative potentials in Apr.-June due to lowering of the water depth (< 5 cm). Soil pH values measured on wet soil samples ranged from 7.0 to 7.5 throughout the study so that adjustment

Table 6. Mass removal efficiency of orthophosphate-phosphorus (1993-1994).

Plants	Cells	July-Sept.	Oct.-Dec.	Jan.-Mar.	Apr.-June
		%			
J/S†	1-2	97	82	62	64
S/T‡	2-3	98	84	83	78
S-R*	5-6	99	-	-	-

† J/S = *Juncus sp.* and *Scirpus sp.* (rush and bulrushes)
‡ S/T = *Sparganium sp.* and *Typha sp.* (bur-reed and cattails)
* S-R = Soybean-Rice

to pH 7 was not required to interpret the data. These observations are consistent with the increased level of NO_3-N in the Oct.-Dec. and Jan.-Mar. effluents (Table 3).

Yet, a pre-wetland oxidative step seems advantageous for increased, sustainable nitrogen and phosphorus removal. This oxidation might be accomplished by treatment of the wastewater via overland flow which has an aerobic/anaerobic layer at the soil surface (Carlson et al., 1974). In overland flow, the water film is only a few mm thick and in close contact with the nitrifying population of the soil surface. Overland flow also offers the advantage of denitrification of the formed NO_3-N in the underlying anaerobic layer.

SUMMARY

1. Quarterly DOC means in the inflow ranged from 9 to 15 mg L^{-1}. Mean outflows ranged from 7 to 32 mg L^{-1}. Higher values of DOC in the outflow indicated that at times the wetlands were a source of C. The treatment efficiency was variable and particularly low during autumn and winter (5 to 65%).

2. Quarterly means of NH_3-N inflow ranged from 22 to 49 mg L^{-1}. Mean outflow NH_3-N throughout the year ranged from 3 to 1 mg L^{-1}, and from 8 to 1 mg L^{-1} for the rush/bulrushes and bur-reed/cattails cells, respectively.

3. Nitrate-N was below 2 mg L^{-1} in the inflow. During the warmer periods, NO_3-N in the discharge waters was <0.5 mg L^{-1}. In the cooler period of Oct. 1993 - Mar. 1994, NO_3-N in discharge waters ranged from 2 to 10 mg L^{-1}.

4. Mean inflow *o*-PO_4-P ranged from 6 to 12 mg L^{-1}. In the initial period (July-Sept.), outflow values were about 0.2 mg L^{-1}, but thereafter they ranged from 2 to 4 mg L^{-1}.

5. Total mass removal for nitrogen and phosphorus during this first year was 90 and 80%, respectively.

6. Soil redox values were very low in July - Sept. 1993 period (+100 to -250 mV) for all plant communities even though the wastewater was diluted > 10 times, and DOC was below 20 mg L^{-1}. Oxidation was attained in the cattails/ bur-reed cells (3 and 4) in Apr. - June 1994 when water depth was shallow (< 5 cm).

7. Redox values were much more oxidized from Oct. 1993 - Mar. 1994 for rush/bulrushes (cells 1 and 2), and the presence of NO_3-N in the discharge effluent indicated that increased O_2 solubility and decreased microbial O_2 demand had a measurable effect on the wetland processes. Similar effect was found in cattails/bur-reed (cells 3 and 4), but redox potentials were much lower during this period with lower concentrations of NO_3-N in the effluent.

8. It appears that more oxygen would be beneficial for long-term removal of both nitrogen and phosphorus.

9. Enhanced oxidation, treatment efficiency, and sustainability might be obtained by sequencing other land treatment methods such as overland flow and rapid infiltration with constructed wetlands.

10. A pre- and/or post-wetland treatment for phosphorus may be desirable.

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