SWINE WASTEWATER TREATMENT BY CONSTRUCTED WETLANDS IN THE SOUTHEASTERN UNITED STATES[1]

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ABSTRACT

Swine production is a major enterprise in the Eastern Coastal Plain, and constructed wetlands have received considerable interest as a method of swine wastewater treatment that could decrease the amount of land required for application of wastewater. This study was undertaken to investigate the capacity of constructed wetlands that contained either natural wetland plants or water-tolerant agronomic plants to treat swine wastewater. Six wetland cells (4 × 30 m) were constructed in Duplin Co., NC, in 1992. One set of two cells contained rush and bulrushes, and another set of two cells contained bur-reed and cattails. The third set of two cells contained flooded rice and soybean grown in saturated-soil culture. A nitrogen loading rate of 3 kg ha^{-1} day^{-1} was used during the initial seven months (June-Dec); plant growth was excellent. The redox conditions of the wetland soils during this start-up period were highly reducing. These reducing conditions may inhibit N loss by nitrification and denitrification as well as decrease the long-term phosphorus removal efficiency. However, during this initial period, treated effluent concentrations of nitrogen and phosphorus were low and could have met discharge requirements in some areas. Some of the ammonia-N may have been nitrified especially in the soybean and rice cells. As the temperatures became cooler, redox potential became more oxidized; and nitrification began to occur. Nitrate was most likely denitrified during the colder months, but the rate of denitrification was not sufficient to eliminate nitrate from the discharge water. Rice yield was 2.8 Mg ha^{-1}, and groups V and VI soybean yielded 1.9 and 3.3 Mg ha^{-1}, respectively. Long-term data over annual cycles for varying crop and hydraulic conditions are needed to assess the treatment sustainability.

INTRODUCTION

In the past, when only a few animal producers were scattered across the landscape, assimilation of waste into standard agricultural production was neither particularly difficult nor significant to nutrient enrichment of regional ecosystems. However, swine production has become a major enterprise in the Eastern Coastal Plain (ECP). In 1990 Sampson Co., NC, and contiguous Duplin Co. were the largest and third largest swine producing counties in the USA (NC Agric. Stat. Div. 1990). Swine production is now a major contributor to the animal waste load of the ECP.

Large quantities of nutrient (in the form of feed) are brought into the ECP each year, and a major portion of these nutrients remains in the form of waste. This can contribute to nutrient enrichment of the agricultural ecosystems. Therefore, wastewater disposal must be accomplished in a reliable and sustainable manner to avoid significant environmental damage to shallow ground

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waters and nutrient-sensitive streams of the coastal environment (Evans et al. 1984, Hubbard and Sheridan 1989, Stone et al. 1989, 1992).

Swine wastewaters are highly concentrated in nutrients (C, N, and P), and their liquid nature makes the cost of transporting or pumping very expensive. Thus, disposal can be a difficult problem for producers that have limited land near their swine operations. Constructed wetlands have received considerable interest 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 natural wetland plants or water-tolerant agronomic plants in constructed wetlands to treat swine wastewater.

MATERIALS AND METHODS

Wetland Cell Layout

Six, 4 × 30-m, wetland cells were constructed in Duplin Co., NC, in 1992 for swine wastewater treatment. The six cells were divided into three parallel sets of two end-on-end cells (Fig. 1). The cell bottoms and side walls 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 at about 15 cm.

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 2700 (ISCO, Lincoln, NE) samplers 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 (Campbell Scientific, Logan, UT) with three multiplexers was installed for hourly acquisition of flow, weather parameters, and soil redox potential data. The water sampler combined hourly samples into daily composites.

Plant Materials

Four cells were planted to natural wetland vegetation in 1992. One set of two cells (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 *T. latifolia*). Estimates of plant biomass were obtained monthly from three random 0.25 m^{-1} 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.

Physico-Chemical Analysis

Water samples were analyzed for electrical conductivity (EC) and pH by electrometric methods. Nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), total Kjeldahl nitrogen (TKN), ortho-phosphate (O-PO_4), total phosphorus (TP), total solids (TS), total organic carbon (TOC), and volatile solids (VS) analyses were performed 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. Soluble organic carbon (SOC) was analyzed with a Dhorman DC-190 carbon (C) analyzer (Rosemount, Santa Clara, CA), and chemical oxygen demand (COD) was analyzed by use of the Hach method (Gibbs 1979). Soil redox potential was monitored continuously at 2-, 5-, and 10-cm depths with a total of ninety Pt electrodes arranged in three clusters of five electrodes per cell with one Ag/AgCl reference electrode per cluster (Faulkner et al. 1989). 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.

Nutrient Loads

The continuous flow loading was automated with float control valves in the mixing tank which provided automated loading of the desired proportion of lagoon liquid and dilution water. However, seasonal changes in the concentration of the lagoon caused the inflow concentration to rise in the fall/winter period. Outflow from the mixing tank for loading to the wetland cells was controlled by valves which were periodically, manually adjusted. Effluent from all three wetland series was pumped back to the lagoon in order to avoid any problems with discharge requirements. The lagoon wastewater was pumped onto crop land as needed for storage space. Neither odors nor mosquitos were a problem.

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 to a 1:15 ratio with fresh water and applied at an N rate of 3 kg ha^{-1} day^{-1}. This 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 evaporation transpiration 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. Wastewater was not applied to the soybean and rice cells during the entire Oct.-Dec. period, and the data for these cells in this period are neither reported nor discussed.

RESULTS

All equipment for pumping, diluting, and measuring flow and distribution worked well and required little maintenance during the start-up period which began in June of 1993. However, freezing weather caused problems from December through February.

During periods of high temperatures and low rainfall, standing water was not maintained throughout cells 2 and 4. Vegetation planted in cells 1 and 2 remained predominant; whereas, intrusion of voluntary species occurred in cells 3 and 4. As temperatures decreased, standing water was maintained in all wetland cells.

A half section of 6-inch PVC pipe was used to distribute flow across the width of the constructed wetland cells. However, channelization occurred near the discharge of the second cell in each series during periods when standing water was not maintained throughout that wetland cell.

Vegetative growth in the four natural vegetation wetland cells was very good. The estimates of above-ground dry matter production for cells 1, 2, 3, and 4 were 23.4, 17.9, 10.2, and 8.4 Mg ha^{-1}, respectively. This is similar to the above ground biomass for emergent aquatic macrophytes reported by DeBusk and Ryter (1987). The rice yield was 2.8 Mg ha^{-1} which is an acceptable production yield. Mean seed yields of Groups V and VI soybean were 1.9 and 3.3 Mg ha^{-1}, respectively. Soybean yields were not as high as those reported by Cooper (1992), but they were higher than the state average, and there were substantial cultivar differences including some high yields. The soybean cultivar Young yielded 3.8 Mg ha^{-1}.

The electrical conductivity (EC) of the applied wastewater was significantly lowered by flow through all of the wetland cells. The mean EC of inflow and outflow during June - September was 589 and <240 þS cm^{-1}, respectively. The Oct.-Dec. period was somewhat higher with inflow and outflow EC values of 743 and < 500 þS cm^{-1}, respectively. This decreased EC during flow through the cells indicated that there was a lowering of total electrolytes - probably by several mechanisms including precipitation, soil fixation, plant uptake, incorporation into soil organic matter, ammonia volatilization, and denitrification. Additionally, the lower biological activity was indicated by a smaller decrease in EC during the colder period.

Average daily pH values ranged from 7.5 to 8.1 throughout the study. However, higher pH values may have occurred as a result of diurnal algal activity. These higher short-term pH values together with high summer temperatures could have induced some NH_3-N volatilization.

The inflow mean for soluble carbon was 12 mg L^{-1}, and the outflow means ranged from 7 to 17 and 11 to 19 mg L^{-1} for the summer and fall seasons, respectively. Wide temporal ranges were observed because the anaerobic lagoon effluent and wetland waters were sometimes significantly diluted by rainfall. Redox potential ranges (+100 to -250 mV, adjusted to the H electrode) indicated strong reducing conditions in all wetland cells during June-Sept. These conditions were unfavorable for nitrification. Thus, NH_3-N remained the prevalent nitrogen form. Limited nitrification also prevented significant subsequent loss of nitrogen by denitrification. The reducing conditions, lack of nitrification and denitrification, and high ammonia-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. time period were more oxidative than the summer values (some depths > + 500 mV). This observation is consistent with the increased level of nitrate in the Oct.-Dec. effluent.

Mean ammonia-N concentrations in the wastewater during the June-Sept. period decreased from 21 mg L^{-1} to 2 mg L^{-1} after treatment in the rush/bulrushes (cells 1 and 2) or bur-reed/ cattails (cells 3 and 4), and it decreased to 0.2 mg L^{-1} after treatment in the soybean and rice cells (Table 2). The mass removal of ammonia-N by wetlands with all three vegetative communities was over 99%. The substantial decrease was probably from plant absorption and NH_3-N volatilization. However, some of the ammonia-N may have been nitrified especially in the soybean and rice cells. The ammonia-N concentration in inflow wastewater was 47 mg L^{-1} during the Oct.-Dec. period when plant growth was dormant, but the rush/bulrush and bur-reed/cattail cells still treated wastewater to mean concentrations of 2 and 7 mg L^{-1}, respectively. This was possible because of increased nitrification/ denitrification.

Mean nitrate-N concentrations were low in the inflow wastewater during the entire study because of the anaerobic conditions in the lagoon (Table 3). Very little nitrate-N was accumulated in the treated wastewaters during the June-Sept. period; inflow and outflow mean concentrations were 1.0 and 0.1 mg L^{-1}, respectively. These low nitrate-N concentrations, along with the low redox conditions and the presence of ammonia-N in the final effluent, suggest that very little nitrification occurred. However, in wetlands, nitrification 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 conclusion can be made about the extent of nitrate-N loss by denitrification. Nitrates were present in the outflow during the Oct.-Dec. period; mean values for the rush/bulrush and bur-reed/cattails cells were 4 and 5 mg L^{-1}, respectively. These values betoken that the decreased microbial respiration and increased O_2 solubility associated with the cooler weather allowed sufficient oxygen for increased nitrification or decreased nitrate removal from denitrification and plant uptake.

During the warmer periods, it appears that even the shallow-highly-diluted swine wastewater in this free-water-surface wetlands caused sufficient oxygen demand and diffusion reduction to curtail the aerobic process of nitrification. Thus, an oxidative step during warmer time periods seems advantageous for increased, sustainable nitrogen 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, Hunt and Lee 1976). In overland flow, the water film is only a few mm thick and in close contact with the nitrifying population of the soil surface. Thus, nitrification should occur rapidly, particularly if overland flow treatment was done after treatment in the wetland cell had reduced the organic content of the wastewater. Overland flow also offers the advantage of denitrification of the formed nitrate in the underlying anaerobic layer.

In the wastewater, phosphorus was present mostly in the form of orthophosphate (Table 4). We believe that its effective removal was predominately by plant uptake, precipitation, and sorption to the soil substrate. Mass removal by wetland with all three vegetative communities was over 99% during the June-Sept. period. However, during the Oct.-Dec. period, phosphate removal was not as good. Mean inflow orthophosphate was 12 mg L^{-1}, and outflow values were 4.1 and 3.1 mg L^{-1}, for the rush/bulrush and bur-reed/cattails cells, respectively.

SUMMARY

Estimated above ground dry matter productions for the first vs second cells of rush/bulrush and bur-reed/cattail were 23.4 vs 17.9 and 10.2 vs 8.4 Mg ha^{-1}, respectively. Rice yield was a respectable 2.8 Mg ha^{-1}, and the soybean cultivar Young yield of 3.8 Mg ha^{-1} was substantially higher.

The redox conditions of wetland soil during the June-Oct. period were highly reduced. The presence of ammonia-N in the discharge effluent and the very low concentrations of nitrate-N throughout the wetlands suggest that the cell did not support nitrification which must occur before removal of nitrogen by denitrification. Nitrates were present in the outflow during the Oct.-Dec. period. These values suggest the presence of sufficient oxygen for increased nitrification or decreased nitrate removal from denitrification and plant uptake. However, nitrification and denitrification in wetlands occur at the interface of aerobic and anaerobic zones, and more detailed measurements are needed before a conclusion can be made about the extent of nitrate-N loss by denitrification.

The low N loading rate of 3 kg ha^{-1} day^{-1} was chosen because it is a currently recommended level that seems to be reasonable for sustainability. The preliminary results presented are for this loading rate during the first seven months of operation. The treated effluent concentrations of nitrogen and phosphorus were low and could have met discharge requirements in some areas; however, longer-term research is needed. Phosphorus is of concern on a long-term basis since the highly reducing conditions may lower the removal efficiency.

An oxidative component and a reductive component in sequence will be necessary for nitrogen removal. If it does not occur in the natural wastewater-plant-soil interface of the wetland cell, it could be produced by construction of an oxidative component and recycling of the effluent. In any case, more extensive and thorough data obtained over annual cycles for varying crop and hydraulic conditions will be necessary to determine if constructed wetlands can reduce the land for swine wastewater treatment.

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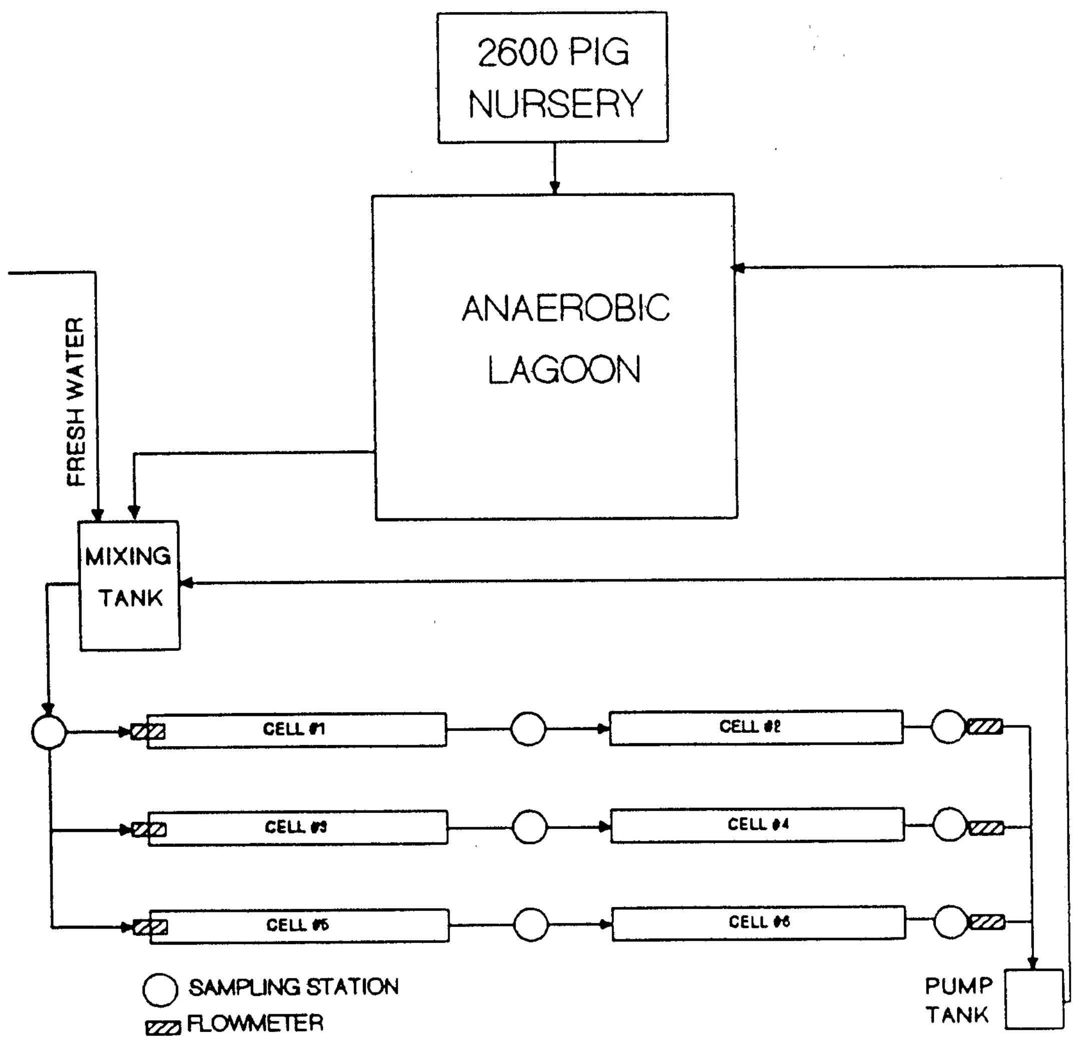

Figure 1. A schematic of the pig nursery, lagoon and constructed wetlands.

Table 1. Characteristics of non-diluted wastewater from the anaerobic lagoon.			
PARAMETERS	UNITS	MEAN	STD. DEV.
pH		7.53	0.14
TS	(g kg^{-1})	1.86	0.47
VS	(g kg^{-1})	0.73	0.32
TOC	(mg L^{-1})	235	124
COD	(mg L^{-1})	737	237
BOD_5	(mg L^{-1})	287	92
TKN	(mg L^{-1})	365	41
NH_3-N	(mg L^{-1})	347	52
NO_3-N	(mg L^{-1})	0.04	0.03
TP	(mg L^{-1})	93	11
o-PO_4	(mg L^{-1})	80	9

Table 2. Mean and standard deviation for NH_3-N of daily composite wastewater samples.					
PLANTS	SAMPLER	June - Sept.		Oct. - Dec.	
		Mean	SD	Mean	SD
		mg L^{-1}			
	INFLOW	21	6	47	23
J/S†	CELL 1	4	4	15	13
	CELL 2	2	4	2	2
S/T‡	CELL 3	3	3	21	17
	CELL 4	2	2	7	8
SOYBEAN	CELL 5	8	6	-	-
RICE	CELL 6	0.2	0.1	-	-

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

Table 3. Mean and standard deviation for NO_3-N of daily composite wastewater samples.					
PLANTS	SAMPLER	June - Sept.		Oct. - Dec.	
		MEAN	S.D.	Mean	S.D.
		mg L^{-1}			
	INFLOW	1.0	0.3	1	0.4
J/S†	CELL 1	0.1	0.1	8	5.3
	CELL 2	0.1	0.1	4	2.6
S/T‡	CELL 3	0.2	0.2	6	4.0
	CELL 4	0.1	0.1	5	5.0
SOYBEAN	CELL 5	0.8	0.2	-	-
RICE	CELL 6	0.1	0.1	-	-

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

Table 4. Mean and standard deviation for *o*-PO_4 of daily composite wastewater samples.					
PLANTS	SAMPLER	June - Sept		Oct. - Dec.	
		MEAN	S.D.	Mean	S.D.
		mg L^{-1}			
	INFLOW	4.0	0.8	12	5.8
J/S†	CELL 1	1.0	0.6	6.4	4.0
	CELL 2	0.2	0.1	4.1	2.6
S/T‡	CELL 3	0.7	0.6	6.2	4.8
	CELL 4	0.1	0.1	3.1	3.1
SOYBEAN	CELL 5	2.0	0.4	-	-
RICE	CELL 6	0.3	0.2	-	-

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