

TREATMENT OF SWINE WASTEWATER USING A SATURATED-SOIL-CULTURE SOYBEAN AND FLOODED RICE SYSTEM

A. A. Szögi, P. G. Hunt, F. J. Humenik

ABSTRACT. *Constructed wetlands have potential for treatment of livestock wastewater, but they generally contain wetland plants rather than agronomic crops. We evaluated two agronomic crops, saturated-soil-culture (SSC) soybean and flooded rice, in a constructed wetland system used for swine wastewater treatment. Both crop production and treatment efficiency were evaluated from 1993 to 1996 in two 4-m × 33.5-m constructed wetland cells that were connected in series. The first cell contained SSC soybean — four cultivars planted in a randomized complete block design with four replications. Flooded rice 'Maybelle' was planted in the second cell. From the first to fourth year, wastewater application rates were gradually increased to obtain rates of 2.0 to 8.8 and 0.5 to 2.2 kg ha⁻¹ d⁻¹ for total N and P, respectively. The best soybean grain and dry matter yields were 4.0 and 9.1 Mg ha⁻¹, respectively. These were obtained with soybean 'Young' at the lowest wastewater application rate. Increasing total N loading rates and the associated higher NH₄-N concentrations depressed soybean seed yield and dry matter production. On the other hand, both rice grain and dry matter production were stable over the application range; mean values were 4.0 and 10.9 Mg ha⁻¹, respectively. Nutrient mass reductions were good; removal values increased linearly with loading rates ($y = 0.69N \text{ load} + 0.45$, $R^2 = 0.99$ and $y = 0.45P \text{ load} + 0.20$, $R^2 = 0.95$). At the highest loading rate, the system removed 751 and 156 kg ha⁻¹ yr⁻¹ N and P, respectively. It appears that the SSC soybean and flooded rice system could be useful for liquid manure management in confined livestock production. The system produced comparable treatment to systems with natural wetland plants; moreover, the soybean and rice are marketable crops. However, the flooded rice seems to be the more robust component for high wastewater application rates.*

Keywords. *Paddy rice, Nitrogen, Phosphorus, Wastewater treatment, Constructed wetlands, Swine manure, Glycine max, Oryza sativa.*

Constructed wetlands are a potentially important method for liquid manure treatment (Hammer, 1989; Hunt et al., 1995; Cronk, 1996; Szögi et al., 1999). Unfortunately, they typically use wetland plants that have little value as a harvestable crop. An alternative to wetland plants might be the use of crop or forage plants that are tolerant to flooding or saturated-soil conditions. Such crops would also provide the benefit of crop production and nutrient assimilation. Up to the present time, only limited information is available on constructed wetland systems designed to both treat livestock wastewater and provide an agricultural crop.

In the U.S.A., one demonstration facility used constructed wetlands that contained Chinese water chestnut (*Eleocharis dulcis* Trin.) as part of an integrated system for treatment of swine wastewater (Maddox and Kingsley, 1989). The system provided high nitrogen and phosphorus removal rates which reduced the land area requirement for terminal application. In China, a land treatment system for municipal wastewater used flooded rice (*Oryza sativa* L.) to maximize application of wastewater and crop yields per unit area (Ou et al., 1992). In New Zealand, reed sweetgrass (*Glyceria maxima* Holb.) in constructed wetlands was used for both dairy wastewater treatment and production of forage (Tanner, 1996). These examples show that the simultaneous crop or forage production and water treatment are a plausible management option for constructed wetland systems.

We were interested in two of the major grain crops, soybean (*Glycine max* Merr.) and rice, as alternative to wetland plants in constructed wetlands used for swine wastewater treatment. Flooded rice was thought to be a viable option for wastewater treatment since processes for nutrient removal in rice fields are similar to those occurring in natural wetlands (Patrick et al., 1985; Gersberg et al., 1986; Faulkner and Richardson, 1989). Rice fields have the ability to remove N and P through processes that result from the interaction between plants and flooded soil (Reddy and Patrick, 1984).

Even though soybean do not tolerate prolonged flooded soil conditions, they grow well under saturated-soil-culture (SSC) conditions (Hunter et al., 1980; Scott et al., 1989;

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Hartley et al., 1993). Saturated-soil-culture conditions, which promote similar nutrient removal processes as in rice fields, can be created on raised flat beds that are surrounded by furrows (Troedson et al., 1985). In these furrows, irrigation water is kept at a constant level below the surface of the bed to provide a thin aerobic surface soil layer in which abundant root growth occurs (Lawn and Byth, 1989).

Although the agronomic performance has been documented for SSC soybean and flooded rice when fresh water is used, little is known about their performance under livestock wastewater application. The objective of our study was to evaluate both crop production and swine wastewater treatment in a constructed wetland system containing SSC soybean and flooded rice.

MATERIALS AND METHODS

STUDY SITE

To evaluate the agronomic performance and nutrient removal capacity of a SSC soybean-flooded rice land treatment system for swine lagoon wastewater treatment, we conducted a four-year pilot study from 1993 to 1996 at a swine farm in Duplin County, North Carolina. The production unit, a 2,600-pig nursery (average weight = 13 kg), used a flushing system to recycle liquid from a single-stage anaerobic lagoon (fig. 1). The average liquid volume of the lagoon was 4100 m³ with a residence time of 120 d. Typically, the lagoon liquid contained 365 mg L⁻¹ TKN (> 95% NH₄-N) and 93 mg L⁻¹ total P (TP).

WASTEWATER TREATMENT SYSTEM

The wastewater treatment system consisted of two 4-m × 33.5-m wetland cells connected in series (fig. 1). The two wetland cells were constructed by the Natural Resources Conservation Service and Murphy Farms, Inc., as part of a USDA Water Quality Demonstration project (Hunt et al., 1993). The cells were created by soil excavation. Once the topsoil was removed, the bottoms of the wetland cells were sealed with 0.30-m compacted clay and covered with 0.25 m of loamy sand topsoil. In the first cell, soybean in SSC were grown on leveled, raised beds that were surrounded by 0.15-m-deep furrows in which the water level was maintained about 0.05 m below the bed surface (fig. 2).

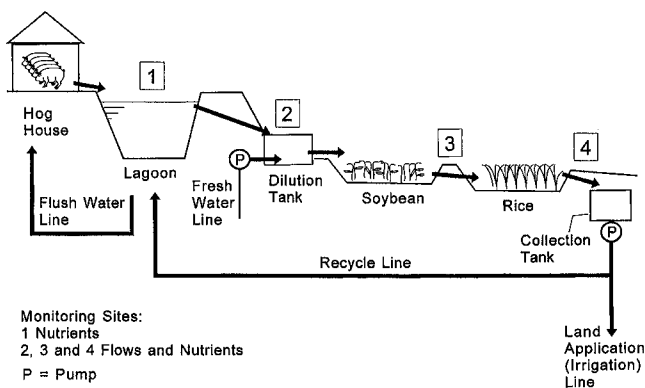


Figure 1—Schematic of saturated-soil-culture soybean and flooded rice water treatment system.

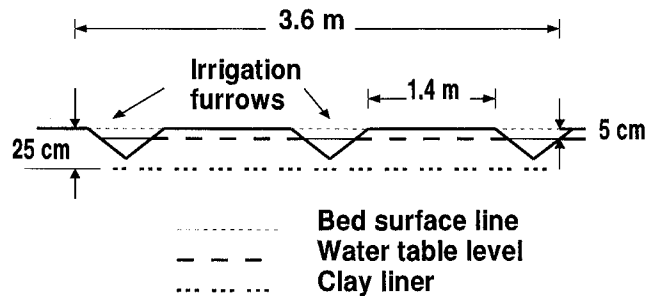


Figure 2—Cross-section schematic of treatment cells with saturated-soil-culture.

The SSC bed in the first wetland cell was divided into four blocks with six 1.4-m × 2.7-m plots in each block. A completely randomized block design with four replications was thus arranged using soybean cultivar as the plot treatment. Soybean cultivars were then randomly placed in the plots each year. The second wetland cell was graded to a 0.2% slope and planted to flooded rice. It was divided into four equal blocks for sampling. The first cell received the inflow of wastewater. The second wetland cell collected the outflow from the first cell. The effluent from this second cell was accumulated in a tank and pumped back to the lagoon. Inflow and outflow were measured with V-notch weirs using ultrasonic depth detectors (Control Electronics, Morgantown, Pa.). Water from the lagoon was recycled to flush the pig nursery house. Excess treated effluent due to rain was land applied.

SOIL CONDITIONS AND PLANTING

Each year prior to planting, random samples were taken for soil testing analyses (Donohue, 1992). In addition, seven 0.20-m-depth soil samples were taken for total nutrient analysis (four among the soybean and three among the rice). The soil texture was loamy sand (86% sand, 10% silt, and 4% clay), and bulk density was 1590 kg m³. Four-year average total Kjeldahl N was 298 mg kg⁻¹; and Mehlich-3 plant available P and exchangeable potassium were 65 and 12 mg kg⁻¹, respectively. The soil in both wetland cells remained saturated during the entire crop season due to continuous wastewater application. In the wetland cell planted to soybean, a thin top soil layer < 20-mm-thick remained unsaturated. In this soil layer, gravimetric soil moisture measurements indicated an average total water filled porous space of about 93%. Soil pH values in saturated or flooded soil ranged from 6.5 to 7.0.

Soil aerobic/anaerobic conditions were evaluated by measuring soil redox potential (Eh) with a total of thirty Pt electrodes. The electrodes were arranged in clusters of five; three clusters were installed per wetland cell with one Ag/AgCl reference electrode per cluster. All electrodes were tested for quality control before and after field measurements with quinhydrone in pH 4.0 and 7.0 buffer (Bohn, 1971). Electrodes were inserted into the soil at 20-, 50-, and 100-mm depths. A data logger was used for hourly acquisition of soil Eh. Redox potential values were corrected by adding the potential of the Ag/AgCl reference electrode, +200 mV, to the mV reading. Well-aerated soils are characterized by Eh > +400 mV, whereas flooded soils have redox potentials as low as -300 mV (Patrick et al., 1985).

Determinate growth habit soybean cultivars were planted at the rate of 13 seeds m⁻¹ of 71-mm-wide rows (~750,000 plants ha⁻¹) each year (table 1). The initial soybean cultivars consisted of three maturity group Vs (Essex, Holladay, and Hutcheson) and three maturity group VIs (Brim, Centennial, and Young). Since the first year mean seed yields for maturity group V and VI cultivars were 1.9 and 3.3 kg ha⁻¹, the group V cultivars were dropped from the experiment. A fourth small-seeded cultivar 'Pearl' was planted from 1994 to 1996 at the same seeding rate. In 1995 and 1996, nodulating (No) and non-nodulating (NNo) isolines of 'Lee' soybean were also grown in SSC to estimate both N₂ symbiotic fixation and N uptake according to the 'difference' method of Vasilas and Ham (1984).

In the second wetland cell, rice cultivar Maybelle was planted at a rate of 15 g m⁻² on the same dates as the soybean (table 1). The rice seed was broadcast on dry soil (dry-seeded), flushed with wastewater two or three times for plant establishment, and later flooded permanently at the five-leaf stage up to a maximum water height of 0.15 m. The wetland cells were drained before harvest. At harvest all soybean and rice plants were collected from both cells.

For the crop season (May-October), the four-year average daily temperature was 23°C and the average total precipitation was 710 mm.

WASTEWATER APPLICATION RATES

The daily hydraulic loading rates ranged from 8 to 11 mm d⁻¹. A mean residence time of six days was estimated according to Watson and Hobson (1989). This hydraulic load and wastewater concentration produced the desired nutrient load. Since high concentrations of ammonia can be damaging to plants, the N application rate was initially kept low; the 1993 N application rate was 2 kg N ha⁻¹ d⁻¹. It was obtained by >10-fold dilution of wastewater with well water (fig. 1). Well water ratios were derived weekly after determination of lagoon NH₄-N concentrations. The well water used to dilute the lagoon wastewater contributed only negligible amounts of total N (< 0.8 mg L⁻¹) and total P (< 0.04 mg L⁻¹). After 1993, dilution ratios were decreased to evaluate soybean and rice tolerance of higher ammonia concentration in the wastewater. Nitrogen and P loading rates applied from 1993 to 1996 are shown in table 1.

SOIL, PLANT, AND WATER QUALITY ANALYSES

Soil samples were air dried for nutrient analysis. All harvested plant materials were oven-dried at 65°C to constant moisture. Grain yields were reported on a 130 g

Table 1. Planting dates, wastewater application, and loading rates for the saturated-soil-culture soybean and flooded rice treatment system used for swine wastewater treatment in Duplin Co., N.C.

Year	Planting Date	Wastewater Application Starting Date	Daily Nutrient Load (kg ha ⁻¹ d ⁻¹)		Number of Days with Wastewater Application	Total Nutrient Applied (kg ha ⁻¹ yr ⁻¹)	
			N	P		N	P
1993	13 May	1 June	2.0	0.5	110	222	52
1994	24 May	13 June	4.8	1.0	115	557	122
1995	22 May	15 June	6.5	1.7	119	773	202
1996	22 May	24 June	8.8	2.2	112	983	246

kg⁻¹ (13%) moisture basis. Soil and plant tissue samples were ground and subsequently digested using a block digestion technique (Gallaher et al., 1976). Total Kjeldahl N (TKN) and TP in plant and soil digestates were determined by automated analysis (Technicon Instruments Corp., Tarrytown, N.Y.).

We assessed the treatment performance of the soybean-rice system by monitoring water quality at three sites (fig. 1): the inlet (site 2), the outlet of the SSC soybean (site 3), and the outlet of the flooded rice (site 4). The outflow from flooded rice constituted the treated effluent. Three-day composite water samples were obtained using automated samplers to sample on a 8 h basis. The samples were kept at 4°C until chemical analyses. Two sets of samples were taken at each time: one to an acidified bottle, and another to a non-acidified bottle. Nutrient analyses were conducted on the acidified samples. All water quality analyses were performed using EPA methods (U.S. EPA, 1983). Soluble compounds were determined in samples filtered with a 0.45-µm pore-size membrane and analyzed for NH₄-N, nitrate/nitrite-N (since nitrites were very low, we will hence refer to their combination as nitrates), soluble reactive P (SRP), and pH. Unfiltered samples were analyzed for TKN and TP. All forms of N and P were determined by automated analysis (Technicon Instruments Corp., Tarrytown, N.Y.). Total N (TN) was the sum of TKN plus NO₃-N concentrations.

NUTRIENT BALANCE

The treatment efficiency expressed as a *global nutrient budget* was calculated for TN and TP by the product between the inflows and outflows and its respective nutrient concentrations (Kadlec and Knight, 1996). Nutrient balances were calculated for the SSC soybean-flooded rice system using data from monitoring sites 2 and 4 and for the flooded rice using data from sites 3 and 4 (fig. 1). Nutrient concentrations were considered negligible in precipitation. Groundwater inflow or outflow was considered small because of the clay liner. Therefore, the mass balance closure was reduced to:

$$\frac{\Delta M}{\Delta t} = \frac{Q_i \times C_i - Q_o \times C_o}{A} \quad (1)$$

M = mass of a given nutrient per unit area treated by the system (it included the nutrients in soil, plant, and microbial biomass. In the case of N, it was also assumed that losses by denitrification and ammonia volatilization were included.)

ΔM/Δt = change in mass (*global nutrient balance*) of a given nutrient per unit time

Q_i and Q_o = inflow and outflow of wastewater per unit time

C_i and C_o = inflow and outflow nutrient concentration
A = area

Analysis of variance (proc ANOVA), regression (proc REG), means, standard deviations, and standard errors (proc MEANS) were determined using SAS software (SAS Institute, 1988).

RESULTS AND DISCUSSION

AGRONOMIC PERFORMANCE

The highest mean soybean dry matter production (9.1 Mg ha^{-1}) and grain yields (3.5 Mg ha^{-1}) occurred in the first year when the wastewater application rate was the lowest (table 2). Average dry matter and grain yields decreased considerably as the N load increased during the three subsequent years: $y = -0.9 \text{ N load} + 10.6$, $R^2 = 0.95$ and $y = -0.4 \text{ N load} + 4.3$, $R^2 = 0.99$, respectively. The dry matter response is shown in figure 3. Plant lodging (a condition in which the main stem is bent over to the point that it often touches the soil surface as a result of pod and leaf weight and/or wind) was a significant contributor to the low dry matter production and grain yield in 1996. The four-year average grain yield was $2.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$.

Among the soybean cultivars, the highest grain yield was 4.0 Mg ha^{-1} for cultivar Young in 1993. This cultivar also had the highest grain yields in the subsequent three years. From 1993 to 1996, average grain yields (Mg ha^{-1}) obtained for the soybean cultivars were the following: Young (2.6 ± 0.5); Brim (2.3 ± 0.5); Centennial (1.9 ± 0.4); and Pearl (1.6 ± 0.6). According to the analysis of variance, differences in yield by cultivar were significant, but cultivar \times year interactions were not significant. This indicated that there were consistent cultivar advantages in SSC conditions with swine wastewater application as shown by the higher average yields of cultivars Young and Brim.

Table 2. Summary of aerial dry matter accumulation and grain yield of saturated-soil-culture soybean and flooded rice for four crop seasons 1993-1996

Year	Soybean*		Rice	
	Dry Matter† (Mg ha^{-1})	Grain Yield (Mg ha^{-1})	Dry Matter (Mg ha^{-1})	Grain Yield (Mg ha^{-1})
1993	9.1	3.5	9.4	3.4
1994	5.4	2.4	11.5	4.7
1995	5.2	2.0	11.1	3.0
1996	2.7	0.9	11.6	5.0
Mean	5.6	2.2	10.9	4.0
S.E.‡	1.3	0.5	0.5	0.5

* Average of all soybean cultivars.

† Dry matter = grain + stalks.

‡ Standard error of the mean.

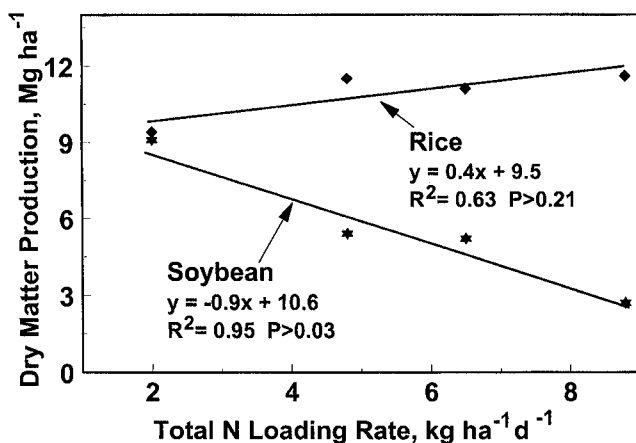


Figure 3—Relationship of soybean and rice dry matter accumulation to total N loading rate.

Rice had mean dry matter accumulation and grain yield of 10.9 and 4.0 Mg ha^{-1} , respectively (table 2). Notwithstanding the fact that rice received less N than soybean, it responded very differently to high N loads. Rice was somewhat positively affected in dry matter accumulation by increased wastewater application rates, and the grain yield was not decreased with increased N loading. The regressions for N load versus dry matter and grain yield were $y = 0.4 \text{ N load} + 9.5$, $R^2 = 0.63$ and $y = 0.2 \text{ N load} + 3.3$, $R^2 = 0.18$, respectively. The dry matter response for rice is also shown in figure 3. The highest dry matter accumulations and grain yields 11.6 and 5.0 Mg ha^{-1} , respectively, were obtained in the year with the highest application rates. As with soybean, one of the major factors that negatively affected rice yields was plant lodging which was related to seasonal conditions and lower grain yields in 1993 and 1995.

NUTRIENT EXPORT BY PLANTS AND RETENTION BY SOIL

Export by Plants. Maximum removal of nutrients from wastewater via plant uptake depended upon the plant nutrient assimilative capacity and plant tolerance to toxic nutrient levels such as ammonia. Under flooded conditions, rice plants can effectively use $\text{NH}_4\text{-N}$ as the N source (Goyal and Huffaker, 1984). Soybean plants can also effectively utilize $\text{NH}_4\text{-N}$ as a N source provided that the root zone pH is above six (Tolley-Henry and Raper, 1986). In addition, soybean plants can accumulate a significant portion of their N by symbiotic N fixation. Research has shown that symbiotic N fixation is stimulated and sustained under SSC (Guafa et al., 1993; Troedson et al., 1989). Nitrogen fixation normally provides 50 to 90% of accumulated N to irrigated soybean in soils of the SE Coastal Plains (Matheny and Hunt, 1983). In 1995 and 1996 when the N application rates were $> 6.5 \text{ kg ha}^{-1} \text{ d}^{-1}$, our nodulating Lee soybean accumulated $156 \text{ kg ha}^{-1} \text{ N}$. The non-nodulating soybean accumulated only $83 \text{ kg ha}^{-1} \text{ N}$ (table 3). Thus, $< 55\%$ of the total N accumulated in soybean came from uptake of wastewater N even though the soybean were grown in the relatively high N environment of SSC irrigated with swine wastewater.

In the first year when the application of N was only $2 \text{ kg ha}^{-1} \text{ d}^{-1}$, it is likely that the fixation rate was even higher. This would be consistent with the fact that together the soybean and rice accumulated more N and P than were applied (222 and 52 kg of N and P, respectively, table 4). Additionally, since the soybean had the opportunity to accumulate the N before the rice, it is also possible that insufficient N may have contributed to the low rice yield of 1993.

In the subsequent three years, soybean had no increased N or P utilization because dry matter production decreased. On the other hand, rice N uptake increased. It ranged from

Table 3. Dry matter production and N accumulation by nodulating (No) and non-nodulating (NNo) Lee soybean under saturated-soil culture for wastewater treatment*

	Lee - No	Lee - NNo
Dry matter production (Mg ha^{-1})	$5.7 (\pm 0.3)$	$3.4 (\pm 0.3)$
N accumulation (kg ha^{-1})	$156 (\pm 12)$	$83 (\pm 9)$
N-fixation (%)	$47 (\pm 9)$	

* Data are averages of 1995 and 1996 crop seasons; standard errors of the mean are given in parentheses.

Table 4. Total N and P applied and accumulated in plant tissue of saturated-soil-culture soybean and flooded rice at harvest

Year	Applied		Soybean		Rice	
	N	P	N	P	N	P
	-----kg ha ⁻¹ -----					
1993	222	52	229*	19	187*	42
1994	557	122	207	24	238	53
1995	773	202	154	20	257	40
1996	986	246	98	13	250	51
Mean	635	125	172	19	233	47
S.E.†	163	37	29	2.3	16	3

* Plant accumulation = grain + stalks.

† Standard error of the mean.

238 to 257 during 1994 to 1996. Nevertheless, the increased rice uptake of nutrients was not nearly as great as the increased N in the wastewater, and the relative plant nutrient utilization decreased with increasing loading rates. The uptake of P was similar to that of N except that rice accumulated a higher portion of P relative to N. At the highest application rates (986 and 246 kg ha⁻¹ yr⁻¹ N and P, respectively) soybean utilized < 10% and rice utilized < 25% of total N and P applied to the system. This demonstrated that except at very low loading rates, plant nutrient uptake is not a dominant removal mechanism for wastewater treatment because the loading rates are far in excess of those used by agronomic crops. However, the treatment of the wastewater in constructed wetlands is accomplished by plants, soil, and microorganisms.

Retention by Soil. Soil retention of N was a significant treatment component at all loading rates, and there was no significant difference in the retention of N between the soybean and rice soils. After the four years of wastewater application, 30% of the applied N remained in the soil (fig. 4). On the other hand, phosphorus was initially retained at significantly higher levels in the soil of the SSC soybean than in the flooded soil of the rice (fig. 5). The SSC soybean soil always had a positive accumulation of P, and by the end of the four years of wastewater application it had retained about 15% of the applied P. The flooded rice soil actually exported P during the first two years, but by the fourth year, the flooded rice soil had actually accumulated about as much P as the SSC soybean soil. The increased retention with time may have been related to soil iron components changing to amorphous ferrous-iron

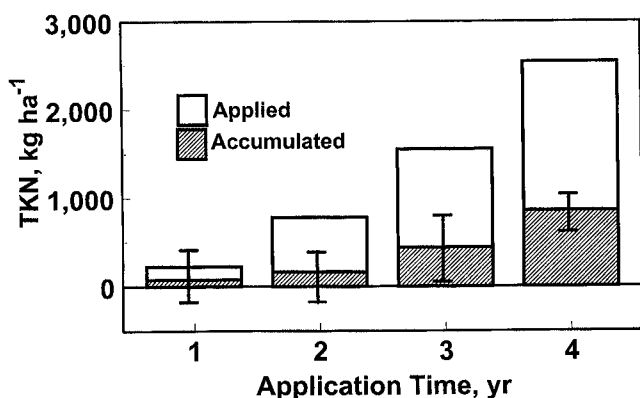


Figure 4—Total N application and soil accumulation for the saturated-soil-culture soybean and flooded rice system over the four years of the experiment.

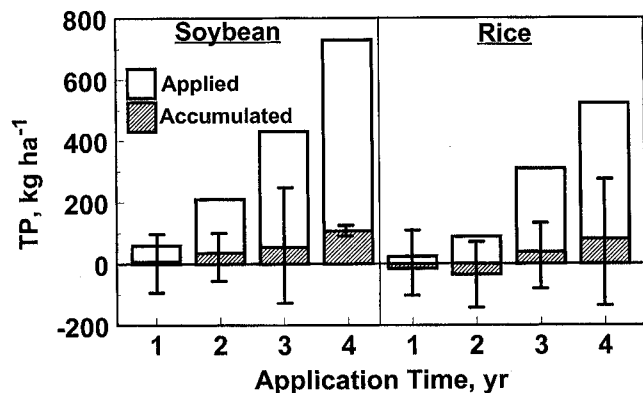


Figure 5—Total P application and soil accumulation for both the saturated-soil-culture soybean and flooded rice components of the treatment system during the four years of the experiment.

hydroxide forms of P as discussed in more detail in the subsequent treatment section. Together, the two cells retained about 25% of the applied P.

TREATMENT PERFORMANCE

In both the wetland inflow and treated effluent, N and P occurred predominantly in the inorganic form. Nitrate-N was always at low levels (< 0.5 mg L⁻¹), and NH₄-N accounted for 89 to 92% of TKN (fig. 6a,b). Soluble reactive P accounted for 87 to 96% of total P (fig. 6c,d).

Initially, almost total mass removal of TN and TP occurred because nutrient loads were low (2 kg N ha⁻¹ d⁻¹ and 0.5 kg P ha⁻¹ d⁻¹, table 5). As stated earlier, at these loading rates, the soybean and rice were accumulating more N and P than was being applied. With higher loading rates in the subsequent three years, the amount of N and P in the effluent increased. However, the total N and P removed by the wetland system also dramatically increased. In 1996 at the highest application rates of 8.8 kg N ha⁻¹ d⁻¹ and 2.2 kg P ha⁻¹ d⁻¹, the total amounts of N and P removed were about 3.5 times higher than in 1993. At these loading rates, the soybean-rice system removed 751 and 156 kg ha⁻¹ yr⁻¹ N and P, respectively. These nutrient removals were much greater than the typical annual nutrient assimilative capacity of 400 to 675 kg N ha⁻¹ and 35 to 45 kg P ha⁻¹ for land treatment systems using bermuda grass (U.S. EPA, 1981). The high P uptake of rice made the removal rates for P even more dramatic.

We also compared the treatment performance of the SSC soybean-flooded rice treatment system with data from free-surface-flow constructed wetlands containing natural wetland plants (CH2M Hill and Payne Engineering, 1997). Specifically, we examined the relationship between nutrient concentrations in the treated effluent and nutrient loading rates (fig. 7). At the loading rate of 8.8 kg TN ha⁻¹ d⁻¹, the concentration of TN in the outflow of the constructed wetlands ranged from 30 to 40 mg L⁻¹, which is similar to the value of 41 mg L⁻¹ predicted for the SSC soybean-flooded rice treatment system (fig. 7). Likewise for phosphorus, the treatment performance of our treatment system was also similar to natural wetland plant systems in the literature. For example, at a loading rate of 2.2 kg P ha⁻¹ d⁻¹, the TP concentration in the treated effluent of the SSC soybean-flooded rice system was 13 mg TP L⁻¹, which is within the effluent concentration range of 6 to

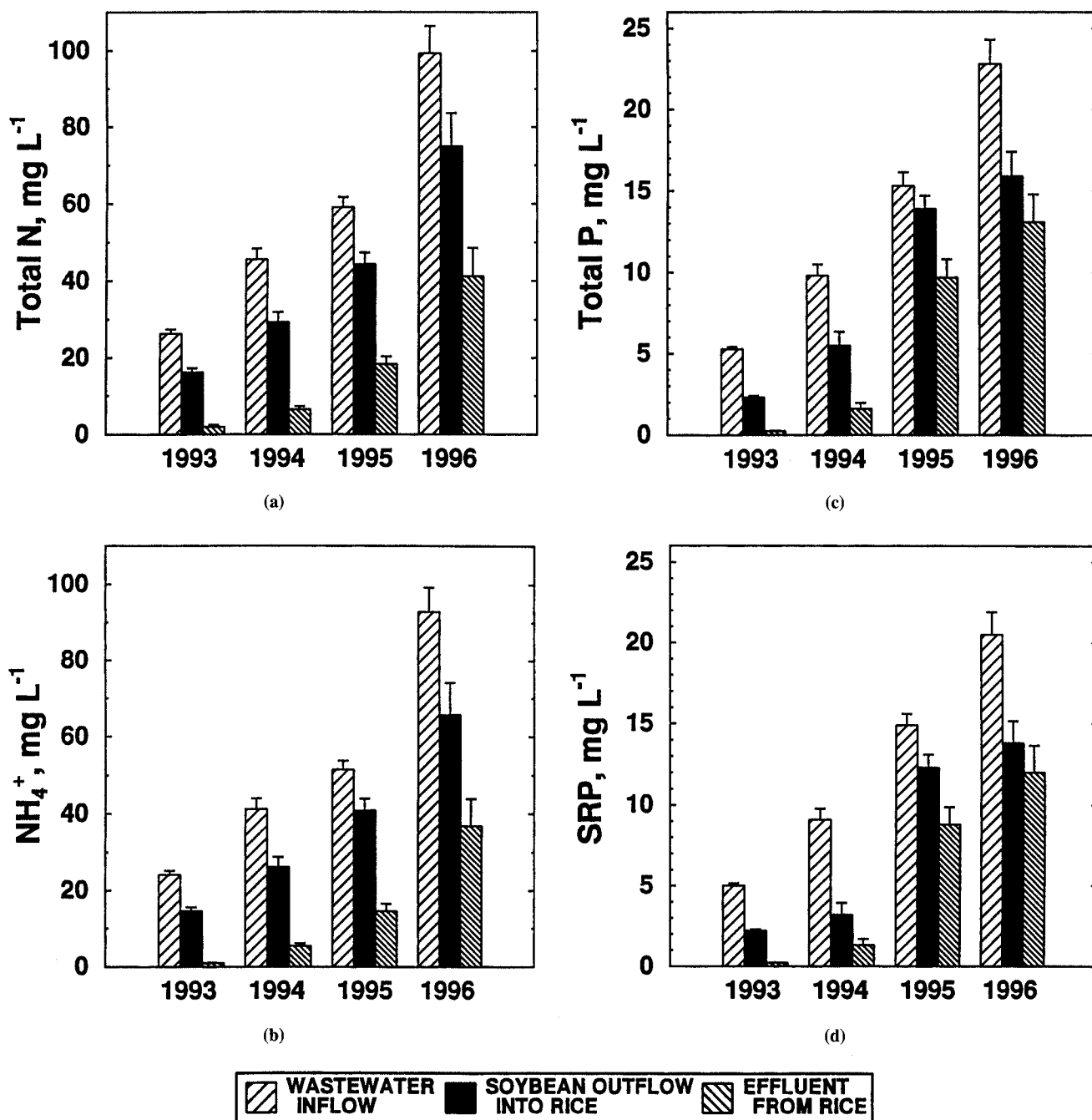


Figure 6—Treatment of swine wastewater by saturated-soil-culture soybean and flooded rice. Figure shows mean inflow and effluent concentrations of (a) Total N, (b) $\text{NH}_4\text{-N}$, (c) total P, and (d) SRP (soluble reactive P) for four crop seasons (1993-1996). Error bars indicate one standard error of the mean.

20 mg P L⁻¹ provided by constructed wetlands with natural plants. As we hypothesized, this data suggest the unique biogeochemical processes that provide high nutrient removal in constructed wetlands are also active in SSC soybean-flooded rice treatment units. For example, rice plants and probably soybean plants can transport atmospheric oxygen through stems and roots. This allows plants to survive anaerobiosis under flooded or saturated soil conditions (Armstrong, 1964; Nathanson et al., 1984; Reddy et al., 1989). This feature also provides oxygen for formation of an aerobic microscopic layer on root surfaces. The formation of two distinct layers (aerobic and

anaerobic) around root surfaces favors microbial N removal by nitrification-denitrification processes.

Aerobic/anaerobic conditions in the soybean and rice cells were evaluated through periodic redox measurements in the subsurface soil (20 to 100 mm depth). These measurements indicated that on the average, the soils were highly reduced. The soil Eh in the soybean soil was -23 ± 255 mV, and the Eh in the rice soil was -124 ± 149 mV. However, redox potentials of $+39 \pm 291$ mV in the upper 20 mm layer of the soybean soil indicated less intense reducing conditions. This large variation in Eh could be due to simple variation in the soil chemical matrix. However, it is somewhat indicative of the coexistence of

Table 5. Summary of nutrient mass balance in the soil-saturated-culture soybean and flooded rice system*

Year	Load In (kg ha ⁻¹ d ⁻¹)	Load Out (kg ha ⁻¹ d ⁻¹)	Mass Nutrient Removal (kg ha ⁻¹ d ⁻¹)
Total N (TN)			
1993	2.0 (±0.2)	0.02 (±0.007)	1.98 (±0.003)
1994	4.8 (±0.2)	1.2 (±0.3)	3.6 (±0.050)
1995	6.5 (±0.4)	1.7 (±0.3)	4.8 (±0.040)
1996	8.8 (±0.7)	2.1 (±2.3)	6.7 (±0.08)
Total Phosphorus (TP)			
1993	0.47 (±0.04)	0.007 (±0.001)	0.46 (±0.002)
1994	1.0 (±0.05)	0.27 (±0.08)	0.73 (±0.070)
1995	1.7 (±0.1)	0.6 (±0.1)	1.1 (±0.050)
1996	2.2 (±0.2)	0.8 (±0.2)	1.4 (±0.070)

* Standard errors of the mean are given in parentheses.

Table 6. Summary of annual nutrient mass balances and nutrient mass removal rates for saturated-soil-culture soybean and flooded rice

Year	Wastewater Mass Loads (kg ha ⁻¹ yr ⁻¹)				Removal (kg ha ⁻¹ yr ⁻¹)				Outflow (kg ha ⁻¹ yr ⁻¹)	
	Applied to Soybean		Passed to Rice*		Soybean		Rice		Total System	
	N	P	N	P	N	P	N	P	N	P
1993	222	52	135	23	87	29	133	22	2	1
1994	557	122	357	64	200	58	219	33	138	31
1995	773	202	576	183	197	19	374	112	202	71
1996	986	246	739	171	247	75	504	81	235	90
Mean	635	125	452	110	183	45	307	62	144	48
S.E.†	163	37	131	40	34	13	82	21	52	20

* Estimated from nutrient concentrations.

† Standard error of the mean.

aerobic/anaerobic soil zones. Such conditions would lead to denitrification almost as rapidly as nitrate was formed. This may explain why NO₃-N concentration was negligible in the effluent.

Although the conditions favor denitrification if nitrate was formed, we cannot eliminate the possibility of significant ammonia losses since we did not measure ammonia volatilization from the surface water. It would seem that these losses were small because the pH of the wastewater was only slightly alkaline (7.6 to 8.2, Anthonisen et al., 1976). Under these conditions, the amount of free NH₃ (gaseous phase) present in the wastewater was lower than 7% of the total N. Additionally, the plant community protected the liquid surface from wind turbulence.

Removal of inorganic P in flooded soils depends on soil sorption properties, pH, and redox conditions (Patrick et al., 1985). At soil pH < 7, P is retained in phosphate form by ferric-iron oxides and hydroxides. Redox conditions are important because redox potentials below +250 mV may cause the reduction of ferric-iron oxides into soluble ferrous-iron, releasing associated P (Faulkner and Richardson, 1989). However, reducing conditions can also cause the transformation of crystalline ferric-iron oxides into amorphous ferrous-iron hydroxides. These ferrous compounds, which provide a large surface area, have a very high P sorption capacity (Patrick and Khalid, 1974; Khalid et al., 1977). This process and the abundance of ferric-iron oxides in the soil of the soybean-rice treatment

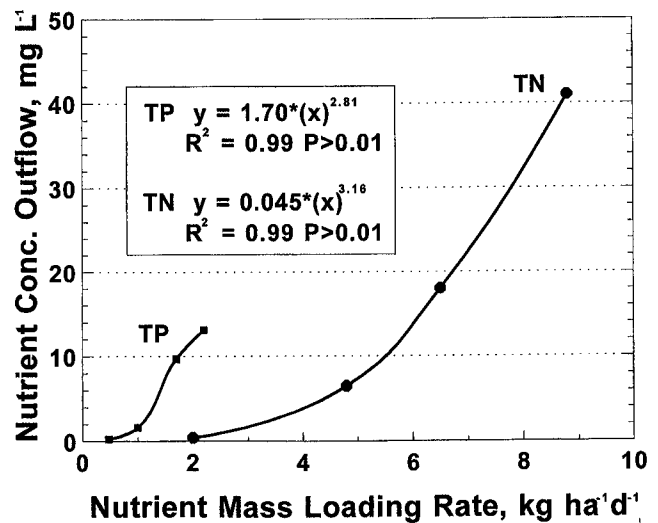


Figure 7—Relationship between nutrient mass loading and nutrient outflow concentration for soil-saturated-culture soybean and flooded rice system for swine wastewater treatment. Each data point is the June-October (1993 to 1996) mean for outflow concentration and daily mass loading.

unit may explain why P mass removal rates increased at higher P loading rates.

The potential use of SSC soybean and flooded rice cultures for swine wastewater treatment depended on both agronomic and wastewater treatment performance aspects. It appears that either system could function alone, but the combination has the advantage of both treatment and crop variability. The actual selection would depend upon the producer, the agronomic culture, and the markets. In either case, the system can doubtlessly be optimized by selection of cultivars and application rates appropriate to the location. Best soybean dry matter production and grain yields were obtained with NH₄-N concentrations in wastewater of about 25 mg L⁻¹, which corresponded with TN loading rates of 2.0 kg ha⁻¹ d⁻¹. However, increasing NH₄-N concentrations, which resulted from higher TN loading rates, depressed total dry matter production (fig. 3). In order to maximize soybean production, N loading rates should not be much higher than 2.0 kg ha⁻¹ d⁻¹. A potential way to avert the ammonia sensitivity and possibly increase denitrification is nitrification of the wastewater prior to its application to the wetland (Vanotti et al., 1998). On the other hand, rice adapted well to NH₄-N concentrations in the wastewater after it had passed through the soybean cell. This was true even when the loading rates were higher. Dry matter production was sustained up to the 8.8 kg TN ha⁻¹ d⁻¹ loading rate applied in our study (fig. 3). At equal loading rates, rice was a better choice than soybean for high levels of nutrient removal. From a treatment performance perspective, the SSC soybean-flooded rice provided an excellent mass nutrient treatment for a wide range of nutrient loading rates. With gradually increasing nutrient loading rates, the system provided both very predictable (R² = 0.99) and high nutrient mass removal rates (fig. 8). For instance, at the highest mass loading rates, 8.8 kg ha⁻¹ d⁻¹ TN and 2.2 kg ha⁻¹ d⁻¹ TP, the system removed 73% of the total applied N and 68% of total applied P.

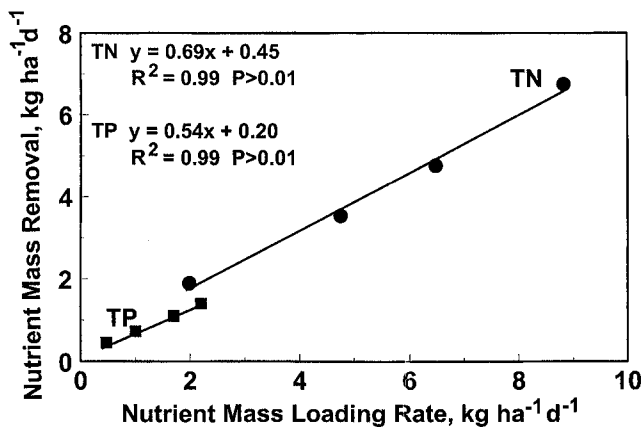


Figure 8—Relationship of both total N and P mass loading vs. mass removal for the saturated-soil-culture soybean and flooded rice system during 1993-1996.

CONCLUSIONS

Soybean plants successfully adapted to SSC that used swine lagoon wastewater. Some cultivars adapted better than others; Young was the best cultivar with 4.0 Mg ha⁻¹ grain yield at the lowest wastewater loading level, 25 mg L⁻¹ NH₄-N. At this loading, dinitrogen fixation accounted for about 50% of the accumulated N. Consequently, soybean did not remove much more than 100 kg N ha⁻¹ yr⁻¹. Soybean grain yield dropped as the wastewater loading increased, and dry matter accumulation decreased linearly with increased concentrations of wastewater. This was likely related to the increased ammonia.

Rice generally performed better than soybean for both dry matter and grain production, 10.9 and 4.0 Mg ha⁻¹ yr⁻¹, respectively. Rice adapted well to NH₄-N concentrations in the range of 16 to 75 mg L⁻¹, and it accumulated a much higher percentage of the applied P than soybean. However, even at the highest application rates, rice utilized slightly less than 250 and 50 kg ha⁻¹ yr⁻¹ of the applied N and P, respectively. Thus, even though crop production was valuable, it was not a significant nutrient removal mechanism in the SSC soybean-flooded rice treatment system, except at the lowest nutrient application rates.

In addition to plants soil accumulation was significant with about 30 and 25% of the applied N and P, respectively, retained in the soil. The additional treatment was likely due to microbial processes, and the high mass nutrient removals obtained with the SSC soybean-rice treatment system were similar to constructed wetlands with natural wetland. Additionally, the soybean and rice of this treatment system are marketable commodities. In wetland systems, soil adsorption and microbial transformations provide nutrient mass removal per unit area much greater than those reported for typical land treatment systems. As such, the SSC soybean and flooded rice systems have the potential to be a useful intermediate between systems with natural wetland plants and traditional crops in the management of confined livestock wastewater.

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