XVII^th World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

EFFECTS OF DRAIN DEPTH ON NITRATE-N AND PHOSPHORUS LOSSES FROM DRAINED AGRICULTURAL LANDS RECEIVING NITROGEN AND PHOSPHORUS FROM ORGANIC SOURCES

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CSBE100224 – Presented at ASABE's 9th International Drainage Symposium (IDS)

ABSTRACT Nitrate and phosphorus losses from drained agricultural lands are an important environmental concern. Installation of subsurface drainage systems at depths more shallow than typical depths has been proposed as a method for reducing nitrate nitrogen (NO3--N) losses in a manner similar to that of controlled drainage. Data were collected from two drainage systems near Plymouth, NC to determine the effect of drain depth on losses of NO3--N and orthophosphate (OP). Drains in the deep system were 1.5 m deep and 25 m apart while drains in the shallow system were 0.75 m deep and 12.5 m apart. Both plots received swine wastewater applications during the first 31 months of the study (October 2002 to April 2005). Overall, the shallow drain system reduced outflows by 17.1% for this period. No significant differences were observed in the NO3--N concentration of the drainage water between the plots; however, the OP concentration in the drainage water of the shallow plot was significantly higher. NO3--N export was reduced by 9.8% at the shallow drain plot during the course of the study. Results of this study were complicated by the application of N and P as swine wastewater which apparently resulted in preferential flow immediately after applications causing relatively high loads of N and P directly to the shallow drains. This phenomenon would not likely occur in cropland where N and P are applied as inorganic fertilizer. This study was continued on the same site for 36 more months (July 2005 through June 2008) using inorganic N and P as fertilizer. This paper reports the effects of drain depth on NO3- -N and OP losses from the study site when organic N and P fertilizer was used.

Keywords: Nitrogen, Nitrate, Phosphorus, Drainage, Shallow drainage, Water quality.

INTRODUCTION Drainage is necessary for food and fiber production from poorly drained soils in eastern North Carolina and throughout much of the world. Increased productivity from drained lands allows us to meet the ever increasing production demand associated with the growing world population. However, with the use of fertilizer and the application of animal and municipal waste to agricultural lands, the need has never been higher to ensure that water quality is being protected.

Nonpoint source pollution has been identified by the NC Division of Water Quality as the primary source of degradation of freshwater rivers and streams in North Carolina. Agriculture has been estimated to account for over 50% of surface water use impairment (Evans, 2004). Researchers, extension workers and state and federal agencies have pursued new Best Management Practices (BMP) that will assist the agricultural community in dealing with non-point source pollution. Two of the primary pollutants from agricultural sites are nitrogen and phosphorus. Nitrogen in the form of nitrate nitrogen (NO_3^--N) is the primary concern in subsurface drainage and groundwater followed by soluble phosphorus or orthophosphate (OP).

Previous research has shown that increasing subsurface drainage intensity can increase the loss of nitrate while decreasing phosphorus losses (Skaggs, 1994). This is because subsurface drainage promotes nitrification which increases the amount of nitrate nitrogen available for leaching. At the same time subsurface drainage reduces sediment and phosphorus losses by decreasing the amount of surface runoff leaving the site.

Although subsurface drainage has been shown to reduce phosphorus losses, soluble phosphorus can still find its way into drainage and ground water. Critical levels of soluble phosphorous have been proposed to be about 0.01 mg/L (Gilliam et al., 1999). Concentrations above this level are assumed to increase the eutrophication of aquatic systems (Sharpley et al., 1987). The concentration of P in drainage waters has been found by several researchers to be from 0.04 to 0.4 mg P/L (Bolton et al., 1970; Calvert, 1975; Baker et al., 1975; Hergert et al., 1981). The EPA recommends that total phosphorus, which is a measure of all dissolved and particulate phosphorus found in water, should not exceed 0.1 mg/L in streams that do not discharge directly into lakes or reservoirs (Muller and Helsel, 1999).

Minimizing Losses Controlled drainage (CD) has been used as a water management strategy to reduce this loss of N to surface waters. A structure, such as a flashboard riser, is positioned in the drainage outlet canal to regulate drainage outflow (Evans et al., 1995). When the flashboards are installed in the riser, the water table is brought closer to the surface. This change in water table depth creates a larger zone in the soil profile where denitrification can occur and reduces the drainage outflow from the system. Gilliam et. al, (1979) reported that it is mainly the decrease of drainage amounts, rather than the reduction of NO_3^--N concentrations, that cause N loads to be significantly reduced in their early CD studies. Controlled drainage requires a relatively flat landscape (slopes <0.5%) and proper management of the flashboards. On more sloping lands, these systems require multiple control structures, and may be too expensive for practical agricultural purposes (Evans and Skaggs, 1989). This has led to the need for research on a system that would have the same benefits as CD without multiple structures and intense maintenance.

Shallow Subsurface Drainage Skaggs and Chescheir (2003) proposed that installation of shallow subsurface drainage systems may reduce NO_3^--N loss in a manner similar to CD. In most conventional drainage systems the drains are placed between depths of 1.0 to 1.5 m. If the drains were to be placed at a depth between 0.75 and 1.0 m, water tables would be raised, relative to the deeper drains, thus creating a larger zone for denitrification similar to controlled drainage. The higher water table created by this system should reduce the subsurface drainage outflow from the system, thus reducing the NO_3^--N loading to surface and shallow ground waters.

Cooke (2002) reported results from the first year of a study on the effect of drain depth in Illinois on a Drummer silt loam, NO_3^--N loading was reduced by 51% by using a 0.61 m deep line at a 15 m spacing versus a 1.22 m deep line at 30 m spacing. Nitrate concentrations in the drainage water were not significantly different between the drainage depths. He stressed the need for further research to validate the conclusions.

Burchell (2003) reported that the total outflow from a shallow drainage system (0.75 m depth and 12.5 m spacing) was reduced by 42% relative to a deep drainage system (1.5 m depth and 25 m spacing). Over the two years period from 2001 to 2002, nearly 8 kg/ha less NO_3^--N was exported from the shallow drains compared to the deep drains. Groundwater concentrations at depths of 90-120 and 150-180 cm depths was significantly lower for the shallow drains (22.9 and 0.1 mg/L, respectively) than for the deep drains (39.1 and 15.5 mg/L, respectively) in 2002.

Sands et al. (2008) reported results from a five year study conducted from 2001 through 2005 in Waseca, MN that focused on the effects of drainage depth and drainage intensity on nitrate export. The soils in this study included Webster and Nicollet clay loams which are classified as poorly drained soils. The results of this study indicated that shallow less intense drainage systems were found to significantly affect drainage volumes (up to a 20% reduction) and therefore nitrate loading (up to 18% reduction) but not nitrate nitrogen concentration. This work suggested that the primary mechanism for the reduction in nitrate export is the reduction in drainage volumes alone.

Shallow drains could increase the export of soluble phosphorus in drainage outflow, since the zone available for phosphorus adsorption to the soil particles may be decreased as drains are placed closer to the soil surface. Another problem that may contribute to an increase in phosphorus losses has been shown by Thomas et al. (1997) from the Broadbalk soil experiment at Rothamsted Research in the United Kingdom. P leaching in drainage water could occur despite large adsorption potential of the soil. He attributed this to the idea of "preferential flow of water flowing down large, possibly permanent cracks in the soil, thus reducing the effective sorption capacity of the Broadbalks subsoil." Bringing the drains closer to the surface may increase the chances for preferential flow of phosphorus and possibly nitrogen in the subsoil. For this reason, further work is warranted on the effect of subsurface drains on nitrate and orthophosphate losses.

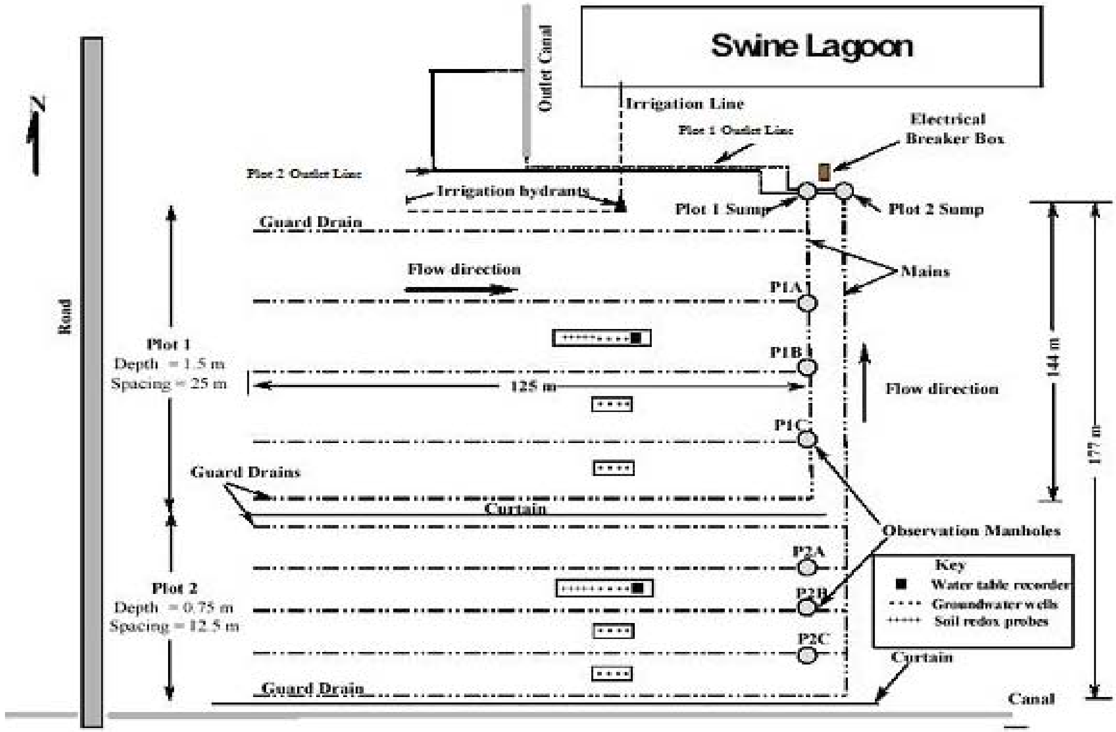

Figure 1. Drainage site schematic

MATERIALS AND METHODS The study site is located in the coastal plain of North Carolina at the Tidewater Research Station in Plymouth. The drainage system was installed on a 2.5 ha beef cattle pasture that is used as a spray field for a swine operation located adjacent to the site. The soil series on the site is Cape Fear Loam (fine, mixed, semiactive, Typic Umbraquualt), which is very poorly drained under natural conditions

Drainage Design Two drainage plots were designed based on DRAINMOD simulations (Skaggs, 1978) and installed during the period of November 1999 and March 2000. Five 125 m long drain lines were installed in each plot. The design drain depth in the deep drainage plot (plot 1) was 1.5 m, with a drain spacing of 25 m (Fig. 1). Drain depth in the shallow drainage plot (plot 2) was 0.75 m, with a drain spacing of 12.5 m. This design holds the drainage intensity the same for both plots, varying both the drain depth and spacing to achieve this condition. The outside drains served as guard drains to hydraulically isolate the middle three drains. Observation manholes were placed at the eastern ends of the three middle drains of each plot to provide access to the drain lines for measurements.

Field Monitoring Systems Field monitoring systems (Fig. 1) consisted of water table recorders, and groundwater monitoring wells. Water table recorders, one for each plot, were installed at the midpoint between drains. Microprocessors were programmed to record water table elevations hourly.

Three well nests were installed in each plot to sample for groundwater quality. Each nest contained four wells screened to collect groundwater samples at the following depths: 30-60 cm, 90-120 cm, 150-180 cm, and 210-240 cm.

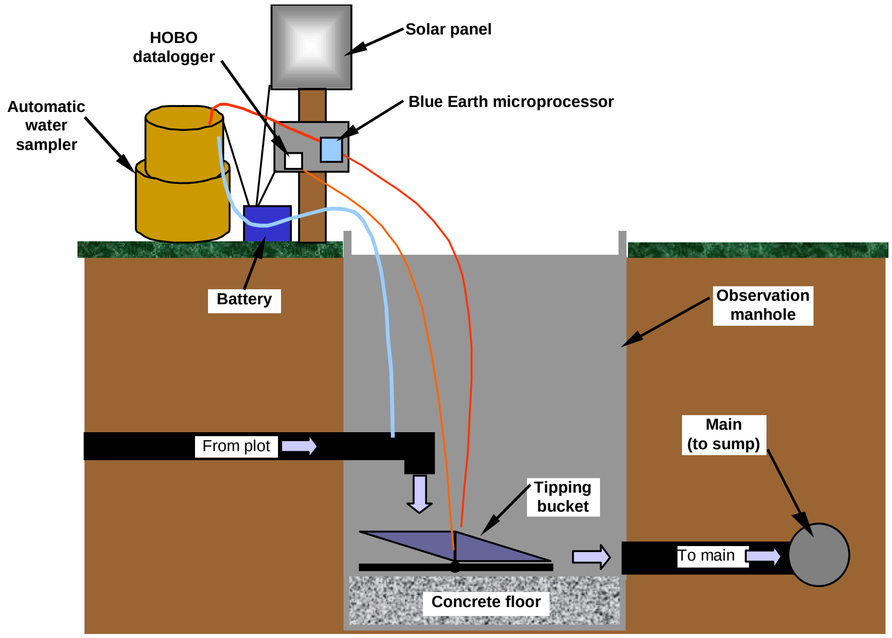

Figure 2. Observation manhole and instrumentation schematic.

An electronic tipping bucket rain gauge was utilized to monitor precipitation and waste irrigation at the site. Additionally, rainfall and irrigation water was measured with a manual rain gauge. A more detailed description of the site and field monitoring system is given in Burchell (2003) and Poole (2006).

Each observation manhole was instrumented to measure drain flow rates and to sample drainage water for water quality analyses (Fig. 2). Because of the limited vertical clearance between the drainage inlet into the manhole and the outlet, streamlined tipping buckets were used to measure drainage flow.

Flow measurements were collected using microprocessors. These microprocessors continuously counted tips but only recorded the hourly sum. Drainage water samples were taken on a continuous, flow-proportional basis with Sigma 900 automatic samplers. The microprocessor was programmed to signal the sampler to take one 100 mL sample for every 950 L of flow.

Nitrogen and phosphorus was applied to the Bermuda and rye grass pasture by irrigating water from the nearby swine waste lagoon. Application rates were based on calibration of the traveling gun irrigation system and the plant available nitrogen (PAN) of the swine wastewater. The PAN applied was 41, 143, 92, and 20 kg PAN/ha/yr in Oct-Dec 2002, 2003, and 2004, and Jan through April 2005 respectively. The amount of P_2O_5 applied on the site was 31, 73, 47, and 25 kg/ha/yr in Oct-Dec 2002, 2003, 2004, and January-April 2005, respectively.

Detailed data collection procedures were described by Burchell (2003) and Poole (2006). All drainage water, groundwater, and precipitation samples were analyzed for nitrate (NO_3^--N) and orthophosphate (OP).

RESULTS AND DISCUSSION

Precipitation Average precipitation for the site is 1310 mm, based on data collected from 1948-2000 at the Tidewater Research Station. Precipitation for the last three months of 2002 was 318 mm which was 26.5% above the historic average of 251.4 mm. In 2003 the precipitation was 1753.2 mm or 33.8 % above average, and in 2004 it was 1293 mm which was almost an average year. There was 311.2 mm of rainfall through April which was 20% below average. Total rainfall during the 31 month period was 3675 mm which was 11 % above the long-term average of 3315 mm.

Hydrology The hourly values for the water table depths for each plot were averaged each year. The difference between the means was assumed to reflect the average difference in water table depth between each plot. From October through December 2002, water table depth in plot 2 (drain depth 0.75 m) was on average 0.2 cm closer to the surface than in plot 1, (drain depth of 1.5 m). In 2003, the water table depth in plot 2 was on average 2 cm closer to the surface than Plot 1. In contrast the water table depth in plot 1 in 2004 was on average 5.9 cm closer to the surface than in plot 2. The water table never fell much below 0.75 m depth the entire year due to heavy precipitation during the summer and fall. This was the primary reason for unusually high water tables in both systems. Finally, from January through April 2005 the water table in plot 2 was 1.4 cm closer to the surface than in plot 1.

The magnitude of subsurface drainage measured in units of depth (cm) from the shallow drains was less, for each year of the study, than that from the deep drains (Fig 3). At the end of 2002, when the precipitation was above normal the shallow drainage volumes were 11.0% less than that from the deeper drains. In 2003, when the precipitation was 33.8% above average the shallow drainage was almost equal to that of the deep drains. In 2004, when the precipitation was near normal, the shallow drainage was 38.7% less than the deep drains. At the beginning of 2005, the shallow drains reduced outflow by 37.2%. On average for the 31-month period, drainage from the deep drains was 28.9 cm greater than from the shallow drains. That is, the shallow subsurface drains reduced drainage outflow during the 31-month period by 17.1%. An analysis of variance indicated that a significant difference in drainage volumes existed in 2004 and 2005, but not at the end of 2002 and 2003 when the precipitation was above normal.

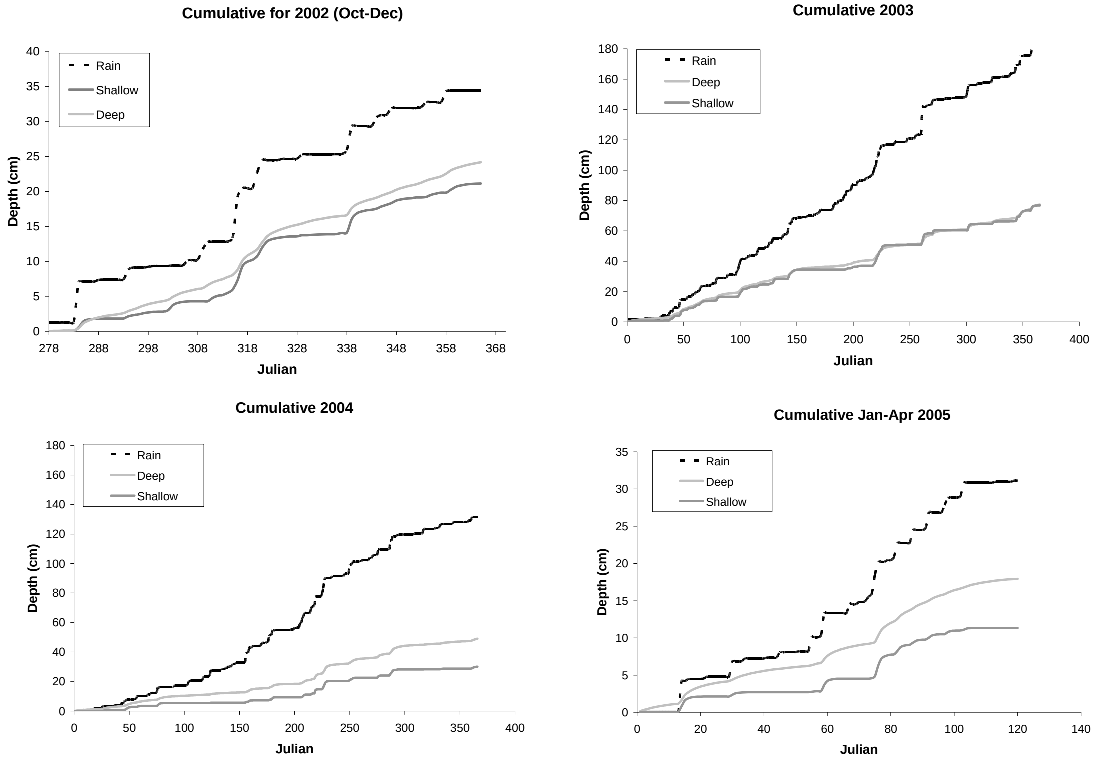

Figure 4. Average cumulative subsurface drainage from Plot 1 and Plot 2.

Nitrate Export The nitrate export from the site was a function of both the nitrate concentration in the drainage water and the drainage volume. The drainage volumes were significantly reduced in 2004 and 2005 when the site experienced normal to below

Table 1. Average NO_3^--N export from a) Plot 1 and b) Plot 2. Standard Deviation in ().

a) Plot 1- Drain depth = 1.5 m, Spacing = 25 m

Drain	**(Oct-Dec) 2002**	**2003**	**2004**	**(Jan-Apr) 2005**	**Total**
			NO_3^--N (kg/ha)		
P1A	35.9	54.0	9.9	6.0	105.8
P1B	33.7	82.4	15.4	8.2	139.7
P1C	35.4	94.6	14.0	9.5	153.5
Average	35.1 (1.22)	77.0 (20.8)	13.1 (2.9)	7.9 (1.8)	133 (24.5)

b) Plot 2- Drain depth = 0.75 m, Spacing = 12.5 m

Drain	**(Oct-Dec) 2002**	**2003**	**2004**	**(Jan-Apr)**	**Total**
			NO_3^--N (kg/ha)		
P2A	33.8	60.3	7.0	2.8	103.9
P2B	37.8	71.2	10.1	4.3	123.4
P2C	29.0	79.6	15.0	8.4	132.0
Average	33.5 (4.4)	70.4 (9.7)	10.7 (4.0)	5.2 (2.9)	120 (14.4)
% Reduction	4.6 %	8.6 %	18.3 %	34.2 %	9.8 %

Note: Significant differences in NO_3^--N export in Plot 2 indicated by * (p=0.10) normal rainfall. However, during the 31-month period, the NO_3^--N concentrations of the drainage water in the shallow system (6.6 mg/L) (n=116) were not significantly greater (p=0.5920) than in the deep system (6.1 mg/L) (n=144). Table 1 shows the average reduction in nitrate export for the study period. An analysis of variance (ANOVA) detected no significant difference between NO_3^--N losses from the deep and shallow plots. Although, the differences were not statistically significant, losses from the shallow drainage system were 9.8 % less on the average during the course of the study.

The ANOVA analysis considered annual losses of NO_3^--N with the two partial years (2002 and 2005) given the same weight as the full years, 2003 and 2004. A separate statistical analysis was performed by grouping the data by month and conducting a paired two-sample t-test for the difference in means. The data are presented in Table 2. The results indicated that the differences between the averages of the two plots were statistically different at the 10% significance level.

Nitrate nitrogen transport from the shallow drains was less than that of the deep drains in all months but May and August. Differences were only 0.43 kg/ha in May, but were nearly 3 kg/ha in August. This reversal in trend, compared to the other months, was mostly due to the large amount of rainfall received during August in both 2003 and 2004. High intensity August storms resulted in large drainage events in both plots and higher water tables. The large rainfall amounts during this month in 2003 and 2004 resulted in a large increase in the cumulative outflow for both plots. The same could be said for May of 2003. Due to the large drainage events that increased the total outflow significantly in a short period, more drainage water from the shallow system very likely followed

preferential flow paths to the drains possibly resulting in the higher export values. Also, the application of lagoon effluent in July 2003 and at the end of August 2003 could have increased NO_3^--N transport by preferential flow to the drains in both plots. If preferential flow occurred, nitrate nitrogen loading would likely be greater from the shallow plot where the drains were only 0.75 m below the surface.

Table 2. Average NO_3^--N export (kg/ha) by month between October 2002 and April 2005

Month	Deep	Shallow	Difference (Deep-Shallow)
		kg/ha	
Jan	5.25	2.23	**+3.03**
Feb	10.30	9.61	**+0.68**
Mar	12.12	9.79	**+2.33**
Apr	9.39	8.05	**+1.35**
May	8.56	8.99	**-0.43**
Jun	3.15	1.40	**+1.76**
Jul	4.96	3.01	**+1.95**
Aug	12.89	15.84	**-2.96**
Sep	9.98	9.60	**+0.38**
Oct	14.13	12.15	**+1.98**
Nov	20.43	17.43	**+3.00**
Dec	21.82	21.67	**+0.15**
Total	**133.0**	**119.8**	**(+1.10)[1]**

[1]Average monthly difference between the deep and shallow plot.

Orthophosphorus Export The orthophosphorus (OP) export from the site was also a function of both the concentration in the drainage water and the drainage volume. The drainage volumes were significantly reduced in 2004 and 2005 when the site experienced normal to below normal rainfall. During the 31-month period, the OP concentrations of the drainage water in the shallow system (0.43 mg/L) (n=118) were significantly greater than in the deep system (0.24 mg/L) (n=144) at the 10% probability level.

The results in Table 3 show no significant difference when using (ANOVA) between the deep and shallow plots except for 2003. However, when the whole study was grouped together significant increases in OP export were found with the ANOVA analysis for the entire period (p=0.0741). The shallow drains during the study exported 103 % more OP than the deeper drains. During 2002 and 2003, the percentage differences were 496 and 1069, respectively. These high percentage increases can most likely be attributed to both the direct flow to the drains after scheduled irrigation events and the frequency and intensity of rainfall at the study site. However, during both 2004 and 2005 the shallow system actually exported less OP than the deeper system. This was due to the average concentrations of OP being relatively close during these periods for both plots. Also, precipitation amounts for the first part of 2005 were well below average which limited leaching of the OP and preferential flow to the drains. The fact that there were fewer irrigation events and thus a lower application of P during 2004 and 2005 may have been the major reason for reduced OP loss from the shallow drains during those years. If the major reason for large losses of OP from the shallow drains was preferential

Table 3. Average OP export from **a)** Plot 1 and **b)** Plot 2. Standard Deviation in ().

a) Plot 1- Drain depth = 1.5 m, Spacing = 25 m

Drain	**(Oct-Dec) 2002**	**2003**	**2004**	**(Jan-Apr) 2005**	**Total**
			OP (kg/ha)		
P1A	0.31	0.15	1.23	0.65	2.34
P1B	0.29	0.36	3.33	0.74	4.72
P1C	0.13	0.17	1.19	0.25	1.74
Average	0.24 (0.10)	0.23 (0.12)	1.92 (1.22)	0.55 (0.26)	2.93 (1.58)

b) Plot 2- Drain depth = 0.75 m, Spacing = 12.5 m

Drain	**(Oct-Dec) 2002**	**2003**	**2004**	**(Jan-Apr) 2005**	**Total**
			OP (kg/ha)		
P2A	0.86	1.97	1.40	0.31	4.54
P2B	2.59	4.10	1.65	0.54	8.88
P2C	0.83	2.01	1.21	0.41	4.46
Average	1.43 (1.01)	2.69* (1.22)	1.42 (0.22)	0.42 (0.12)	5.96 (2.52)
% Increase in	496 %	1069 %	- 26 %	- 23.6 %	103 %

Note: Significant differences in OP export in Plot 2 indicated by * (p=0.10) flow of the irrigated wastewater, a reduction in the frequency of irrigation events could have had a greater effect on losses from the shallow drains than from the deeper drains due to the location of the drains relative to the surface.

A separate statistical analysis was performed by grouping the data by month and performing a paired two-sample t-test for the difference in means. These data are presented in Table 4. The statistical analysis showed that when the data weregrouped by month, the total export differences between the plots were statistically different at the 10% significance level with a p-value of 0.0029. The shallow system consistently exported more OP than the deep system when grouped by month during the study.

Table 4. Average OP export by month between October 2002 and April 2005

Month	Deep	Shallow	Difference (Shallow-Deep)
		kg/ha	
Jan	0.24	0.16	-0.08
Feb	0.25	0.48	0.23
Mar	0.39	0.56	0.17
Apr	0.16	0.34	0.17
May	0.08	0.35	0.27
Jun	0.20	0.17	-0.03
Jul	0.15	0.18	0.03
Aug	0.46	0.92	0.46
Sep	0.20	0.44	0.24
Oct	0.39	0.69	0.30
Nov	0.19	0.75	0.57
Dec	0.22	0.91	0.69
Total	**2.93**	**5.99**	**(+0.25)[1]**

[1]Average monthly difference between the deep and shallow plot.

CONCLUSIONS

Hydrology Outflows for the shallow drains were 17.1% less than the deep drains for the 31-month period. Rainfall was average to well above average for the majority of the study period. The magnitude of subsurface drainage measured in units of depth (cm, cm^3 per cm^2 of surface area) from the shallow drains was less, for each year of the study, than that from the deep drains. An analysis of variance (ANOVA) showed that cumulative drainage volumes from the shallow drains were significantly different from those of the deep drains in only 2004 and 2005. Water table levels were similar for both plots in response to the average to well above average precipitation during the study. The water table at the midpoint between the drains rarely fell below the shallow drain depth of 0.75 m in either plot. Due to the high frequency and amount of rainfall water table depths at a deep drain plots (1.5 m deep) were usually less than 0.75 m.

Nitrate The average concentrations in the drainage water for NO_3^- -N were not significantly different between the two plots. NO_3^- -N concentrations for the deep drain plots averaged 6.1 mg/L and for the shallow drain plots averaged 6.6 mg/L. NO_3^- -N export from the shallow drains was 9.8 % less than from the deeper drains over the course of the study. Average NO_3^- -N export during the 31 months was 120 kg/ha from the shallow drains compared to 133 kg/ha from the deeper drains. Exports from the two plots were not significantly different when the average cumulative values for each plot for each year, or partial year were compared using analysis of variance (ANOVA). However, when export values were analyzed by month and then compared with a paired two-sample t-test for means, there were significant differences between the two systems. That is, when exports measured under similar circumstances (paired by month) were analyzed, the shallow drainage system did show a significant decrease in nitrate nitrogen export compared to the deep system. This decrease was directly related to the reduction in drainage volumes of the shallow system, but not to concentration differences.

Orthophosphorus The average concentrations in the drainage water for OP were significantly higher for the shallow plots. OP concentrations for the shallow drain plot averaged 0.43 mg/L and for the deep drain plots averaged 0.24 mg/L. OP export from the shallow drain system was two times greater than OP export from the deep drain system. Average OP export from the shallow system was 5.96 kg/ha while saw an average export from the deep system was 2.93 kg/ha. The export was significantly different when the average cumulative values for each plot were compared using ANOVA. The export from both plots were paired by month to see how each system responded under similar weather patterns and then compared with a paired two-sample t-test for means. The shallow system continued to show a significant increase in OP export compared to the deep system. Although the shallow system increased the OP export, this increase amounted to just 3.4% of the total phosphorus applied to the site on the average. The increase loss of OP from the shallow system was a function of an increase in concentration. The possibility exists for preferential flow to the drains in this system.

REFERENCES

Baker, J.L., K.L. Campbell, H.P. Johnson, and J.J. Hanway. 1975. Nitrate, phosphorus and sulfate in subsurface drainage water. *J. Environ. Qual*. 4:406-412.

Bolton, E.F., J.W. Aylesworth, and F.R. Hore. 1970. Nutrient losses from tile drains under three cropping systems and two fertility levels on a Brookston clay soil. Can. *J. Soil Sci.* 50:275-279.

Burchell II, M. R. 2003. Practices to reduce nitrate-nitrogen losses from drained agricultural lands. PhD diss. Raleigh, N.C.: North Carolina State University.

Calvert, D.V. 1975. Nitrate, phosphorus and potassium movement into drainage lines under three soil management systems. *J. Environ. Qual.* 4:183-186.

Cooke, R., J. Nehmelman, and P. Kalita. 2002. Effect of tile depth on nitrate transport from tile drainage systems. ASAE Paper No. 022017. St. Joseph, Mich.: ASAE.

Evans, R. O., and R. W. Skaggs. 1989. Design guidelines for water table management systems on coastal plain soils. *Applied Eng. in Agric.* 5(4): 539-548.

Evans, R.O., R.W. Skaggs, 2004. Development of Controlled Drainage as a BMP in North Carolina. *Drainage VIII Proceedings of he Eight International Symposium*. ASAE Publication Number 701P0304. Sacramento, California:

Evans, R. O., R. W. Skaggs, and J. W. Gilliam. 1995. Controlled versus conventional drainage effect on water quality. *J. Irrig. Drain. Eng. ASCE* 116(1): 16-23.

Gilliam, J. W., J. L. Baker, and K. R. Reddy. 1999. Water quality effects of drainage in humid regions. In *Agricultural Drainage*, 801-830. Agronomy Monograph 38. R. W.

Skaggs and J. van Schilfgaarde, eds. Madison, Wisc.: ASA, CSSA, and SSSA.
Gilliam, J.W., R.W. Skaggs and S.B. Weed. 1979. Drainage control to diminish nitrate loss from agricultural fields. *J. Environ. Qual.* 8:137-142.
Hergert, G.W., S.D. Klausner, D.R. Bouldin, and P.J. Zwerman. 1981.Effect of dairy manure on phosphorus concentrations and losses in tile effluent. *J. Environ. Qual*. 10:345-349
Mueller, D.K., and Helser, D.R., 1999. "Nutrients in the Nation's Waters—Too Much of a Good Thing?" *U.S. Geological Survey Circular* 1136. National Water-Quality Assessment Program. Available at: http://water.usgs.gov/nawqa/circ-1136.html
Poole, C. A. 2006. The Effect of Shallow Subsurface Drains on Nitrate-N and Orthophosphorus Losses from Drained Agricultural Lands. MS Thesis. Raleigh, N.C.: North Carolina State University.
Sands, G.R., I. Song, L.M. Busman, B.J. Hansen. 2008. The Effects of Subsurface Drainage Depth and Intensity on Nitrate Loads in the Northern Cornbelt. Trans. ASAE. 5(3):937-946.
Sharpley, A.N., S.J. Smith, and J.W. Naney. 1987. Environmental impact of agricultural nitrogen and phosphorus use. J. Agric. Food Chem. 35:812-817
Skaggs, R.W., M.A. Beve, J.W. Gilliam 1994. Hydrologic and water quality impacts of agricultural drainage. *Crit. Rev. Environ. Sci Technol*. Vol. 24, n 1,pp 1-32.
Skaggs, R. W., and G. M. Chescheir. 2003. Effects of subsurface drain depth on nitrogen losses from drained lands. *Trans. ASAE* 46(2): 237-244.
Thomas, D.G.. Heckrath, and P.C. Brookes. 1997. Evidence of phosphorus movement from Broadbalk soils by preferential flow. In: Tunney, H., et. al. (eds.) Phosphorus Loss from Soil to Water. CAB International, New York, N.Y., pp. 369-370.