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Assessment of a Large Subsurface Controlled Drainage and Irrigation System: III. Water chemistry of the tile effluent and its potential impact on surface water resources

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Abstract: *Controlled subsurface drainage irrigation systems promote crop productivity; however, these land management systems also allow an efficient pathway for the transport of elements from soils to surface water resources. The nitrate and macro-element effluent concentrations from tile-drainage involving a 40 ha controlled subsurface drainage irrigation system are described and compared to soil nitrate availability. Soil nitrate concentrations generally show an increase immediately after soil nitrogen fertilization practices and are sufficiently abundant to promote their transport from the soil resource to the tile-drain effluent waters. The data indicates that: (1) the transport of nitrate-N in tile-drain effluent waters is appreciable; (2) denitrification pathways effectively reduce a portion of the soil nitrate-N when the controlled drainage system establishes winter-early spring anoxic soil conditions, and (3) the best strategy for reducing nitrate-N concentrations in tile-drain effluent waters is adjusting N fertilization rates and the timing of their application. The development of bioreactors for simulating wetland conditions may further limit nitrate concentrations in surface waters because of soil drainage.*

Key Words: *Nitrate, Ammonium, Soil Drainage*

Introduction

The United States Environmental Protection Agency (USEPA) maximum contamination level for nitrate-N is 10 mg/L. There are many reports showing groundwater and surface water nitrate levels exceeding this concentration (Abrahamson et al., 2005 and 2006; Dinnes et al., 2002; Jaynes et al., 2004; Jaynes and Colvin, 2006; Kladivko et al., 2004; Randall et al., 2003). Nitrogen (N) non-point sources commonly include watersheds having N-fertilized row crops, forages and suburban (turfgrass) areas, where the N runoff to tributaries potentially contributes to hypoxia in the Gulf of Mexico (Dinnes et al., 2002).

Sources of surface water N and phosphorus (P) include: (1) surface water runoff from intensively fertilized agricultural fields or urban landscapes, (2) soil erosion, (3) effluent discharge from subsurface drainage systems and (4) subsurface water flow (baseflow) to surface water. Surface water runoff of N and P are particularly associated with watersheds having an intense livestock or poultry presence (Akhtar et al., 2005), where the soils have been heavily fertilized (Moore and Edwards, 2005; Davis et al., 2000) or are in proximity to surface waters (Elliott et al., 2006; Gburek et al., 2000; Langlois and Mehuys, 2003; Page et al., 2005). Nitrate concentrations from subsurface drainages frequently exceed the USEPA maximum contamination levels (Abrahamson et al., 2006; Davis et al., 2000; Randall et al., 2003; Jaynes and Colvin; 2006) and P concentrations may also be a concern, especially where the soils have a low P sorption capacity and elevated P concentrations (Djodjic et al., 2004; Ilg et al., 2005; Page et al., 2005; Anderson and Magdoff, 2005; Langlois and Mehuys, 2003; Stampfli and Madramootoo, 2006). Thus, soil classification and characterization, cropping systems and irrigation/drainage systems interact to produce various pathways for N and P to impact surface water.

Soil testing has previously focused on determining the amount of N and P fertilizer to obtain sound yields. Modern approaches estimate fertilizer requirement for acceptable yields and place limits so as not to exceed the soil's retention capacity (Jaynes et al., 2004; Dinnes et al., 2002). This approach will not inhibit soil losses attributed to erosion; however, this approach will substantially reduce storm runoff nutrient concentrations (Cabrera et al., 2007).

In a review, Dinnes et al. (2002) noted that agricultural investigations aimed at reducing N losses from tile-drained soils include: (1) timing of fertilizer applications and the rates of nitrogen, (2) predicting the mineralization of soil organic matter to better quantify the amount of nitrate present, especially during the non-cropping season, (3) utilization of pre-sidedress nitrate tests and late-season nitrate tests to better calibrate split N applications, (4) improving the efficiency of fertilizer application equipment and encouraging precision fertilization practices, (5) improving production practices that permit the effective use of nitrogen stabilizers, (6) greater use of chlorophyll meters and remote sensing technologies to monitor the crop nutrient status, (7) diversified crop rotations and cover crops that limit N fertilization and reduce nitrate losses, (8) effective plant residue management, (9) establishment and maintenance of riparian buffers, and (10) drainage-control strategies.

Drainage control strategies essential to reducing nitrate-N concentrations in tile-drain effluent waters may be partitioned into two categories: (1) using stop-log boxes to curtail tile-drainage to promote soil water saturation and anoxic soil conditions to encourage denitrification and (2) reduce the leaching potential by maintaining an elevated perched water table.

Kladivko et al. (1999) demonstrated that drainage systems have potential to promote nitrate removal via drainage leachate, particularly if the lateral drainage lines are closely spaced. Fisher et al. (1999) compared subsurface irrigation-controlled drainage systems with open drainage systems and observed that 30–75 cm water table depth maintenance reduced nitrate soil water concentrations and improved corn uptake of nitrogen. Randall et al. (2003) investigated corn-soybean rotations in Minnesota and documented that nitrate leaching correlated with rainfall and that the soybean phase promoted spring nitrate tile-drain discharges because of residue mineralization and residual nitrate concentrations. Randall et al. (2003) also observed that summer intervals exhibited the smallest nitrate leaching because the evapotranspiration rates exceeded the precipitation rates and nitrate accumulated in the subsoil.

Phosphorus studies have centered on P runoff and P leaching (Cabrera et al., 2007; Nelson and Parsons, 2007; Bruland and Richardson, 2004). Organic P may leach and pose a threat to groundwater (Anderson and Magdoff, 2005), whereas Stampfli and Madramootoo (2006) in Quebec showed that subsurface irrigation-controlled drainage systems may have greater losses of total dissolved P than freely drained systems, frequently exceeding 0.03 mg P/L. Davis et al. (2005) in Oklahoma showed that dissolved reactive P somewhat correlated with Mehlich-3P, permitting soil testing to possibly assess the likelihood of P leaching. Conversely, Djodjic et al. (2004) noted that dissolved reactive P could not be predicted by consideration of total P and that preferential water flow pathways did not allow for equilibrium assumptions. Hart et al. (2004), in a review, noted that catchment studies demonstrated 62–91% of surface runoff P is associated with particulate P.

The objectives of this research were to determine nutrient concentrations in tile-drain effluent waters from a subsurface controlled drainage irrigation system and to propose best management practices to limit nitrate and phosphorus impact to receiving surface water bodies.

Materials and Methods

Study Area and Design

The study area is a small portion of the Hubble Creek watershed in Cape Girardeau County (Missouri) and is located on at the Southeast Missouri State University Agriculture Research Center. The study area consists of approximately 40 ha having a subsurface controlled drainage irrigation system (Figure 1). The soil resource is predominately composed of soils of the Wilbur series (Coarse-silty, mixed, superactive, mesic Fluvaquentic Eutrudepts). The Wilbur series consists of deep, somewhat poorly-drained soils having an Ochric-Cambic diagnostic horizon sequence developed in strongly weathered coarse-silty alluvium from mixed materials. The climate is humid continental. The study area and the controlled subsurface drainage/irrigation system are described in Aide et al. (2013a).

Corn (*Zea mays* L.) was planted from 2008 to 2013 on 0.77 meter (30 inch) row-spacing. Phosphorus and potassium (K) fertilization was applied using variable-rate technology based on grid soil sampling. In 2008 to 2011, corn nitrogen fertilization rates were 134 kg/ha (120 lbs/acre) of N as liquid N (28% N-solution) pre-plant, with 179 kg/ha (160 lbs/acre) of N as liquid N applied five weeks post-planting. In 2012, corn nitrogen fertilization rates were 378 kg/ha (344 N lbs/acre) of N as urea applied ½ at one week prior to planting and ½ applied two weeks post planting.

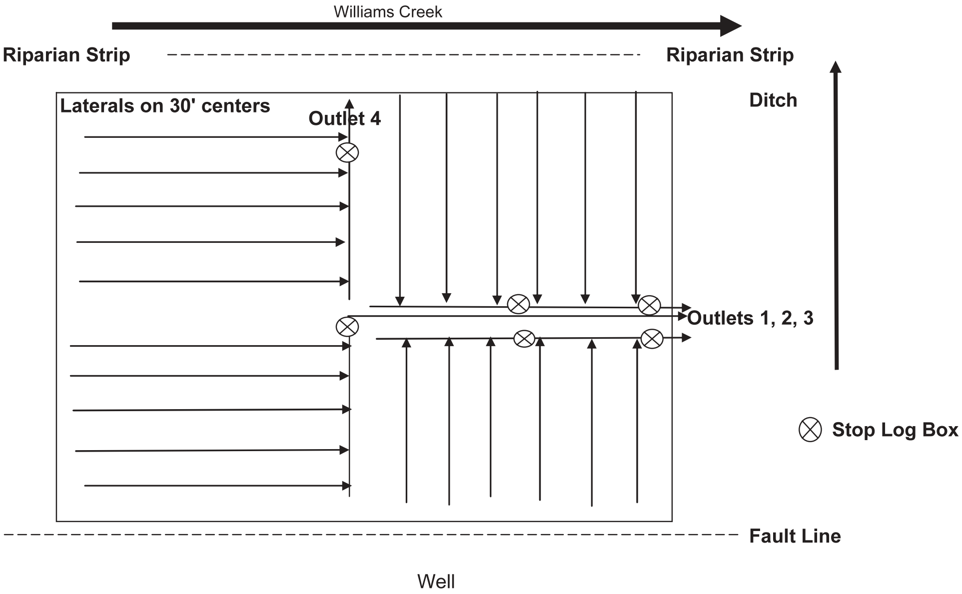
Water Quality Assessment

Water was collected in duplicates using acid washed plastic bottles that were also washed with source area water just prior to collection. Surface water samples consist of water collected from Williams Creek. Samples were immediately taken to the laboratory, filtered (0.45 µm) and one of the duplicates was quantitatively spiked with reagent grade nitric acid for subsequent metal, metalloid, alkali and alkaline earth analysis. The other duplicate was analyzed within 24 hours for nitrate (NO_3-N), phosphorus (PO_4-P), sulfate (SO_4-S), chloride (Cl), total alkalinity ($HCO_3 - CO_3$), ammonium (NH_4-N) and pH. These water quality measurements were performed to characterize the tile drainage effluent waters, water samples from upstream locations on Williams Creek, collected rain water, and irrigation/drainage water from the stop-log boxes. Each sample was characterized for pH, Ca, Mg, K, and Na. A calibrated combination electrode was employed for pH measurement, whereas nitrate and chloride analysis employed ion specific electrodes. Phosphorus, S, Ca, Mg, K and Na were analyzed using inductively coupled plasma emission – mass spectrophotometry.

Soil Nitrate Spatial and Time Distributions

Duplicate soil samples for soil nitrate (NO_3-N) concentrations were obtained on a near weekly to bi-monthly basis and

Figure 1. Illustration of the drainage design and stop-log box locations.



involved soil coring in six inch (15 cm) increments for the upper rooting soil zone (two feet, 60 cm). Soil nitrate and ammonium analyses were performed using the University Missouri-Columbia soil testing laboratory (Delta Center, Portageville, MO). Duplicates were averaged to represent one soil depth data point.

Results and Discussion

Water Quality Assessment

Williams Creek is a calcium carbonate type water, with a pH fluctuating near 7.9 in 2008. (Table 1). Nitrate-N concentrations

Table 1. Mean and coefficient of variation for surface and tile drainage water in 2008.

			-------------------------mg/L			--------------------------	meq/L
Location	Measure	pH	P	SO_4-S	NO_3-N	Cl	Alkalinity
Williams	mean	7.9	0.3	2.3	32	14	3.1
	CV(%)	1.2	18	59	20	41	36
Corn drain	mean	7.2	0.08	12.9	32	55.8	1.7
	CV (%)	4.6	14	27	55	27	23
Rainfall	mean	4.6	0.1	1.7	1.1	1.1	0.1
	Difference	0.2	0.1	1.3	1.2	0.3	0.0
Well Water	value	8	0.08	1	13.7	11.3	0.0

		-------------------------mg/L			-------------------------
Location	Measure	Ca	Mg	K	Na
Williams	mean	54.8	9.7	2.4	4.0
	CV (%)	14	15	3	37
Corn drain	mean	33.9	7.0	1.4	17
	CV (%)	5	13	68	88
Rainfall	mean	1.6	0.2	0.1	0.2
	Difference	0.4	0.1	0.2	0
Well Water	value	49.4	27.7	1.8	2.3

The corn drainage has eight observations, whereas rainfall has two observations and the well water has one observation. CV is the coefficient of variation.

appreciably exceed the US EPA drinking water threshold of 10 ppm NO_3-N, averaging 32 mg NO_3-N/L. Phosphorus concentrations were slightly to moderately in excess of the Canadian water standard (0.03 mg P/L) (Stampfli and Madramootoo, 2006), with the mean Williams Creek PO_4-P concentrations centered near 0.3 mg/L PO_4-P (Table 1).

Drainage tile waters in 2008 are dominantly calcium carbonate type waters. Tile drains providing effluent water from land cultured to corn shows (i) a near-neutral pH, and (ii) the highest mean NO_3-N (32 mg NO_3-N/L). These enhanced tile drain nitrate concentrations reflect the influences of soil organic matter mineralization and nitrogen fertilizer applications.

Time Distribution of Nutrients in Tile-drain Effluent Waters

In 2008 tile-drainage water was collected from the beginning of March to early June, at which time the stop-log boxes were adjusted for irrigation and drainage ceased. The concentrations of P, SO_4-S, Ca, Mg, and K in waters from the individual tile-drains did not exhibit substantial concentration fluctuations during the collection interval. Using tile drain effluent from land cultured to soybeans (*Glycine max* L.) as a reference system, nitrate tile drain effluents were similar from land cultured to corn and soybeans in early to middle March and from middle May to the cessation of soil drainage. Late March to May, nitrate concentrations from late March to May showed appreciable greater nitrate concentrations from land cultured to corn, reflecting soil nitrogen fertilization practices. In all time frames, nitrate concentrations are excessive for maintaining surface water quality.

Nitrate concentrations from tile drains in 2009 (Figure 3) are similar to those of 2008 (Figure 2), showing a maximum nitrate concentration post nitrogen fertilization of corn. All nitrate tile drain concentrations reflect the influence of soil mineralization and soybean residue decomposition and, most importantly, all nitrate concentrations are excessive. Nitrate concentrations from 2010 to 2012 were collected from stop-log boxes during drainage. The collection season from 2010 to 2012 also witness the closure of the stop-log boxes during the winter to (i) prevent land drainage, (2) promote water tables approaching the soil surface, and (iii) augment soil denitrification of existing soil nitrate carryover.

Figure 2. Nitrate-N concentration distributions over time from tile drains.

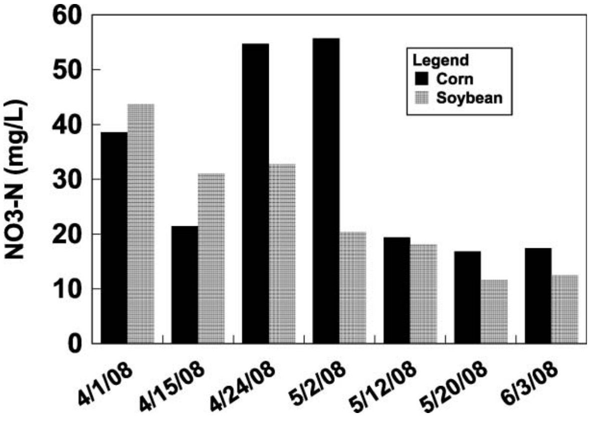
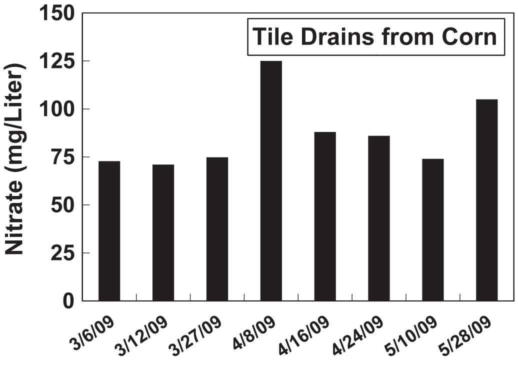


Figure 3. Tile drain nitrate concentrations over time of drainage in 2009.



In 2010, soil drainage occurred from March to early May. Nitrate concentrations were slightly lower for stop-log boxes 3A and 3B (not previously planted to corn). Nitrate concentrations ranged from 8 to 12 mg NO_3-N / liter (Figure 4), suggesting three mechanisms are acting to lower the nitrate concentrations: (i) denitrification limited the soil nitrate reservoir, (ii) the two previous years of drainage operation had reduced the soil nitrate subsurface pool, and (iii) crop production yield increases produced residues having a substantial nitrogen component (Aide et al, 2013b).

Nitrate and ammonium concentrations in 2012 demonstrate greater May nitrate concentrations than March nitrate concentrations, primarily reflecting nitrogen fertilization of corn (stop-log boxes 4A and 4B) and drainage of nitrates present because

Figure 4. Nitrate concentrations from stop-log boxes in 2010.

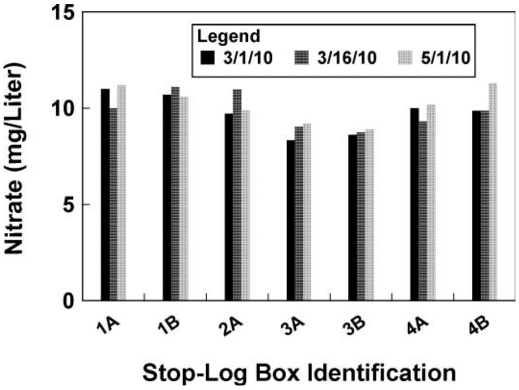
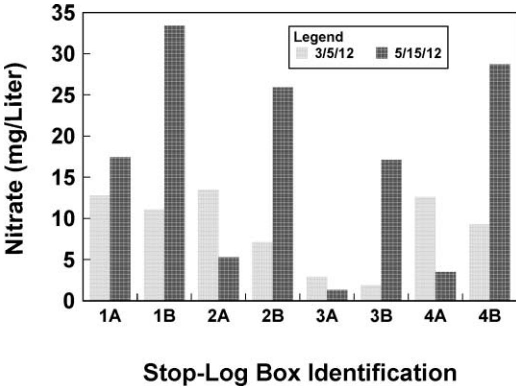


Figure 5. Nitrate concentrations from stop-log boxes in 2012.



of mineralization and residue decomposition (Figure 5). Stop-log boxes 1A, 1B, 2A, and 2B drain land sections cropped to corn in 2011 and cropped to soybeans in 2012. Higher levels of nitrates represent soil nitrate present because of previous (2011) nitrogen fertilization, soil organic matter mineralization and residue decomposition. Soil pH values averaged 6.3 in March and 7.1 in May. Phosphorus concentrations averaged 0.10 mg PO4-P / liter (coefficient of variation was 40%) for March and 0.13 mg PO4-P / liter (coefficient of variation was 84%) for May. Calcium, magnesium, potassium and sodium concentrations were similar to those of 2008 (Table 1).

Ammonium concentrations were greater for stop-log boxes 1A and 1B, land sections cropped to corn in 2011 and cropped to soybeans in 2012 (Figure 6). Interestingly, the winter of 2011–2012 and the cropping season of 2012 were characterized by drought conditions and winter leaching and denitrification reactions were minimized.

Soil Nitrate Time Distributions

The primary intent for measuring soil nitrate concentrations was to qualitatively estimate the soil nitrate-N reservoir.

Figure 6. Ammonium concentrations from stop-log boxes in 2012.

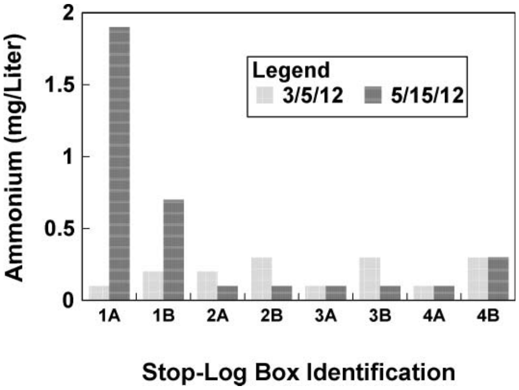
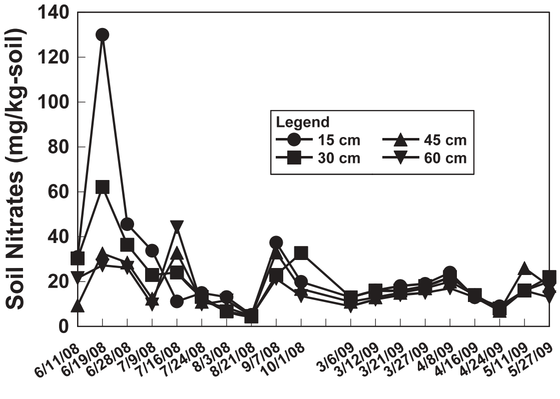


Figure 7. Soil nitrate-N distribution in corn in 2008.



Quantitative sampling would require a much more robust sampling protocol (Mulla and Strock, 2008). Soil nitrate-N was sampled periodically during the growing season to qualitatively assess the magnitude of the nitrate-N soil reservoir, an important N pool that supports plant growth and development and influences nitrate leaching. Soil nitrate concentrations in corn plantings generally increase immediately after nitrogen fertilization. Soil nitrate concentrations in 2008 show a pronounced increase in late June, followed by decreased nitrate concentrations thereafter (Figure 7). The late June nitrate concentrations show the highest concentrations in the surface horizon, with smaller nitrate concentrations at increasing soil depths. In July, nitrate concentrations are greatest at deeper soil layers, inferring soil nitrate leaching.

Soil nitrate concentrations in 2010 show a substantial nitrate pool from May to early July, ranging from 125 to near 60 mg NO_3-N / kg-soil (Figure 8). Soil ammonium concentrations in 2010 show a substantial ammonium pool existing from May to early July, ranging from 17 to near 3 mg NH_4-N / kg-soil (Figure 9). Soil nitrate concentrations in 2012 show a substantial nitrate pool existing from December 2011 to September 2012, ranging from 5 to greater than 80 mg NO_3-N / kg-soil

Figure 8. Soil nitrate-N distribution in corn in 2010.

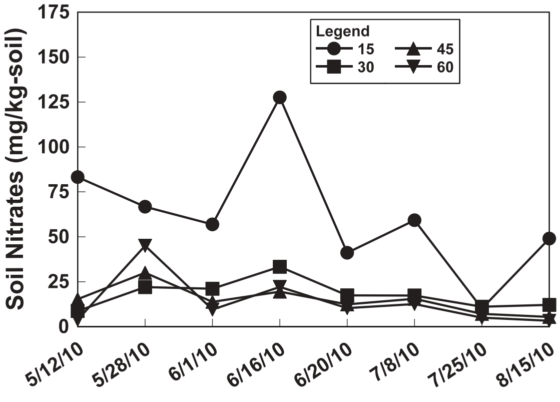
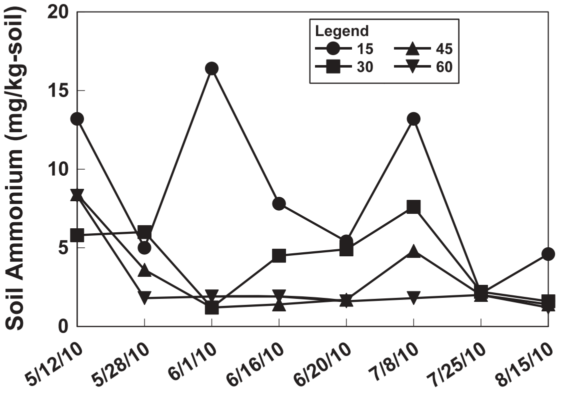


Figure 9. Soil ammonium-N distribution in corn in 2010.



(Figure 10). Soil ammonium concentrations in 2012 show a substantial ammonium pool existing from December 2011 to September 2012, ranging from near 30 to near 2 mg NH_4-N / kg-soil (Figure 11).

Best Management Practices for a Subsurface Controlled-Drainage Irrigation System

Drainage tile effluent waters have appreciable nitrate-N and P concentrations, roughly correlating with soil nitrate concentrations arising from soil fertilization, soil organic matter mineralization and residue decomposition. Key items necessary to limit nitrate concentrations in tile drain effluents include: (i) standardizing soil nitrogen fertilization rates on appropriate yield expectations, (ii) conducting nitrogen fertilization application times when the root system is conducive to nutrient uptake, (iii) the use of fall-winter cover crops to limit nitrate winter carryover, (iv) design and placement of bio-reactors to promote nitrate conversions to organic materials and/or promote denitrification.

Figure 10. Soil nitrate-N distribution in corn in 2012.

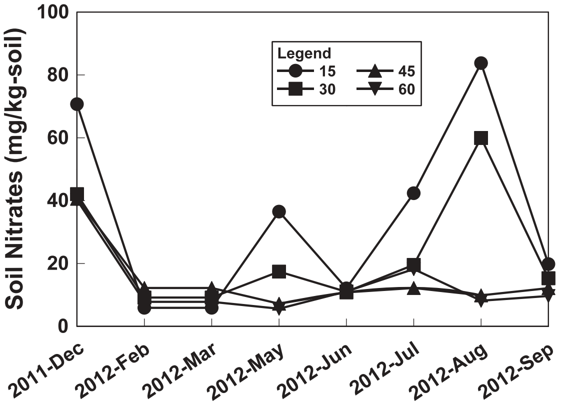
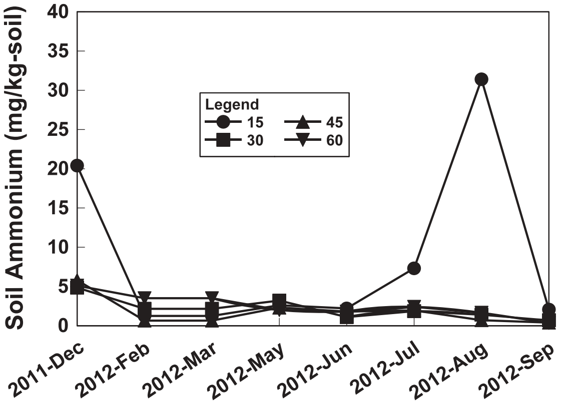


Figure 11. Soil ammonium-N distribution in corn in 2012.



Litherature Cited

Abrahamson, D.A., D.E. Radcliffe, J.L. Steiner, M.L. Cabrera, J.D. Hanson, K.W. Rojas, H.H. Schomberg, D.S. Fisher, L. Schwartz, and G. Hoogenboom. 2005. Calibration of the root zone water quality model for simulating tile drainage and leached nitrate in the Georgia Piedmont. Agron. J. 97:1584–1602.

Abrahamson, D.A, D.E. Radcliffe, J.L. Steiner, M.L. Cabrera, D.M. Endale, and G. Hoogenboom. 2006. Evaluation of the RZWQM for simulating tile drainage and leached nitrate in the Georgia Piedmont. Agron. J. 98:644–654.

Aide, M., I. Braden, D. Mauk, W. Mueller, S. Svenson, and J. Weathers. 2013a. Assessment of a Large Subsurface Controlled Drainage and Irrigation System: I. Design, Soil Properties, and Water Management. Transactions of the Missouri Academy Science. 44/45:000–000.

Aide, M., I. Braden, D. Mauk, W. Mueller, S. Svenson, and J. Weathers. 2013b. Assessment of a Large Subsurface Controlled Drainage and Irrigation System: Corn Performance. Transactions of the Missouri Academy Science. 44/45:000–000.

Akhtar, M., D. McCallister, D. Francis, and J. Schepers. 2005. Manure source effects on soil phosphorus fractions and their distribution. Soil Sci. Soc. Am. J. 170:183–190.

Anderson, B.H. and F.R. Magdoff. 2005. Relative movement and soil fixation of soluble organic and inorganic phosphorus. J. Environ. Qual. 34:2228–2233.

Bruland, G. and C. Richardson. 2004. A spatially explicit investigation of phosphorus sorption and related soil properties in two riparian wetlands. J. Environ. Qual. 33:785–794.

Cabrera, M.L. 2007. Modeling phosphorus in runoff: Basic approaches. *In* De. E. Radcliffe and M.L. Cabrera (eds) Modeling phosphorus in the environment. pp 65–81. CRC Press, Boca Raton, Fl.

Davis, R., H. Zhang, J. Schroder, J. Wang, M. Payton, and A. Zazulak. 2005. Soil characteristics and phosphorus level effect on phosphorus loss in runoff. J. Environ. Qual. 34: 1640–1650.

Davis, D. M., P. H. Gowda, D. J. Mulla, and G. W. Randall. 2000. Modeling nitrate nitrogen leaching in response to nitrogen fertilizer rate and tile drain depth or spacing for southern Minnesota, USA. J. Environ. Qual. 29:1568–1581.

Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils. Agron. J. 94:153–171.

Djodjic, F., K. Borling, and L. Bergstrom. 2004. Phosphorus leaching in relation to soil type and soil phosphorus content. J. Environ. Qual. 33:678–684.

Elliott, H., R. Brandt, P. Kleinman, A. Sharpley, and D. Beegle. 2006. Estimating source coefficents for phosphorus site indices. J. Environ. Qual. 35:2195–2201.

Fisher, M.J., N.R. Fausey, S.E. Subler, L.C. Brown, and P.M. Bierman. 1999. Water table management nitrogen dynamics, and yields of corn and soybeans. Soil Sci. Soc. Am. J. 63:1786–1795.

Gburek, W., A. Sharpley, L. Heathwaite, and G. Folmar. 2000. Phosphorus management at the watershed scale: a modification of the phosphorus index. J. Environ. Qual. 29:130–144.

Hart, M.R., B.F. Quin and M.L. Nguyen. 2004. Phosphorus runoff from agricultural land and direct fertilizer effects: A review. J. Environ. Qual. 33:1954–1972.

Ilg, K., J. Siemens, and M. Kaupenjohann. 2005. Colloidal and dissolved phosphorus in sandy soils as affected by phosphorus saturation. J. Environ. Qual. 34:926–935.

Jaynes, D. and T. Colvin. 2006. Corn yield and nitrate loss in subsurface drainage from midseason nitrogen fertilizer application. Agron. J. 98:1479–1487.

Jaynes, D., D. Dinnes, D. Meek, D. Karlen, C. Cambardella, and T. S. Colvin. 2004. Using the late spring nitrate test to reduce nitrate loss within a watershed. J. Environ. Qual. 33:669–677.

Kladivko, E., J. Frankenberger, D. Jaynes, D. W. Meek, B. J. Jenkinson, and N. R. Fausey. 2004. Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. J. Environ. Qual. 33:1803–1813.

Langlois, J. and G. Mehuys. 2003. Intra-storm study of solute chemical composition of overland flow water in two agricultural fields. J. Environ. Qual. 32:2301–2310.

Moore, Jr., P. and D. Edwards. 2005. Long-term effects of poultry litter, alum-treated litter, and ammonium nitrate on aluminum availability in soils. J. Environ. Qual. 34:2104–2111.

Mulla, D.J., and J.S. Strock. 2008. Nitrogen transport processes in soil. *In* J.S. Schepers and W.R. Raun (eds) Nitrogen in agricultural systems. pp 361–400. Am. Soc. Agronomy, Agron. Mono. #49. Madison, WI.

Nelson, N.O., and J.E. Parsons. 2007. Basic approaches to modeling phosphorus leaching. *In* De. E. Radcliffe and M.L. Cabrera (eds) Modeling phosphorus in the environment. pp 81–104. CRC Press, Boca Raton, Fl.

Page, T., P. Haygarth, K. Beven, A. Joynes, T. Butler, C. Keeler, J. Freer, P. Owens, and G. Wood. 2005. Spatial variability of soil phosphorus in relation to the topographic index and critical source areas: sampling for assessing risk to water quality. J. Environ. Qual. 34:2263–2277.

Randall, G., J. Vetsch, and J. Huffman. 2003. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by time of nitrogen application and use of nitrapyrin. J. Environ. Qual. 32:1764–1772.

Stampfli, N. and C.A. Madramootoo. 2006. Dissolved phosphorus losses in tile drainage under subirrigation. Water Qual. Res. J. Canada 41:63–71.