doi:10.2489/jswc.64.6.400

Nitrogen and phosphorus runoff from cropland and pasture fields fertilized with poultry litter

R.D. Harmel, D.R. Smith, R.L. Haney, and M. Dozier

Abstract: Application of litter and other organic by-products to agricultural land off site of animal production facilities has created both environmental concerns and agro-economic opportunities, but limited long-term, field-scale data are available to guide management decisions. Thus, the objective of this study was to determine the water quality effects of repeated annual poultry litter application as a cropland and pasture fertilizer. Eight years of data collected on ten field-scale watersheds indicated several significant water quality differences based on litter rate (0.0 to 13.4 Mg ha^{-1} [0 to 6 ton ac^{-1}]) and land use (cropland and pasture). On cropland fields, increasing litter rates (with corresponding decreases in supplemental inorganic nitrogen [N]) increased runoff orthophosphate phosphorus (PO_4-P) concentrations but reduced extreme high nitrate nitrogen (NO_3-N) concentrations. Whereas runoff PO_4-P concentrations were somewhat similar between land uses, NO_3-N concentrations were much lower in pasture runoff because of supplemental inorganic N application, reduced nutrient uptake potential, and faster litter mineralization on cropland. Although considerable variability was observed, intra-annual runoff NO_3-N and PO_4-P concentrations generally exhibited curvilinear decay based on time since fertilizer application. In spite of repeated annual litter application and buildup of soil phosphorus (P) at high litter rates, few long-term trends in N and P runoff were evident due to the dynamic interaction between transport and source factors. These results support several practical implications, specifically: (1) combining organic and inorganic nutrient sources can be environmentally friendly and economically sound if application rates are carefully managed; (2) high runoff N and P concentrations can occur from well-managed fields, which presents difficulty in regulating edge-of-field water quality; and (3) change in the animal industry mindset to view by-products as marketable resources could mitigate environmental problems, provide alternative fertilizer sources, and enhance animal industry revenue opportunities.

Key words: agricultural runoff—waste utilization—water quality

Organic animal by-products, such as poultry litter, which is composed of manure and bedding material, can be agronomically effective sources of organic matter, macronutrients, and micronutrients to enhance crop production. Stockdale et al. (2002) provides an excellent discussion of the soil fertility enhancement in organic systems. Motavalli et al. (2003) indicated that a single application of poultry litter can benefit soil physical properties and increase nitrogen (N) availability for several seasons; however, organic fertilizers can lead to degradation of on-site soil quality and off-site water quality if not managed properly (Sharpley et al. 1999). Kingery et al. (1994) reported that long-term, high-rate broiler litter application in Alabama increased concentrations of beneficial organic carbon (C) in the soil but also increased total N, extractable phosphorus (P), copper, and zinc levels, which can be beneficial or detrimental, depending on crop needs, soil properties, and watershed conditions. On a historical research site in Nebraska, Eghball et al. (2002) showed that long-term manure application can build soil P and nitrate nitrogen (NO_3-N) levels. That study also concluded that both recently applied and residual soil nutrients can contribute to nutrient loss with relative contributions depending on the timing of runoff and application. Sharpley et al. (1999) and Haggard et al. (2003) also discussed the potential for excessive losses of both recently applied and residual soil N and P and their contributions to accelerated eutrophication. Thus, proper management is essential to protect the environment by minimizing off-site loss and to achieve maximum agronomic benefit from applied organic fertilizer.

Land application is the most common, and usually the most desirable, method of utilizing the nutrient and organic matter resources in animal manure and litter (USDA and USEPA 1999). Land application occurs either within animal production facilities or off-site at conventional farm and ranch operations that import the manure or litter. The recent expansion of off-site (3rd party) land application sites for poultry litter and other organic by-products has created both concerns and potential solutions with serious on-farm, societal, and environmental implications related to waste utilization. The complex interaction of these factors is described by Janzen et al. (1999) and Turnell et al. (2007). For organic sources to be incorporated into fertilization schemes, they must be cost-effective, preferably in the short-term (Jacks 1954; Stockdale et al. 2002). Dramatic increases in commercial fertilizer costs since 2002 have made organic fertilizers competitive, despite higher transport and application costs (Harmel et al. 2008a). Thus more farmers and ranchers are now considering organic alternatives for agricultural production. The animal industry is also becoming more receptive to distributing litter off-site, as on-site application fields in many areas are reaching agronomic or regulatory thresholds for soil P (Sharpley et al. 2003; Bekele et al. 2006; DeLaune et al. 2006). The resulting increase in land receiving litter application can be a major component in reducing water quality degradation because it is the application of nutrients in organic fertilizers at rates that exceed crop uptake and soil assimilative capacity, even for a short period,

Daren Harmel is a research agricultural engineer for the USDA Agricultural Research Service (ARS), Temple, Texas. **Doug Smith** is a soil scientist for the USDA ARS, West Lafayette, Indiana. **Rick Haney** is a soil scientist for the USDA ARS, Temple, Texas. **Monty Dozier** is the regional program director for Texas AgriLIFE Extension, Bryan, Texas.

Table 1
Land management and watershed characteristics of cropland and pasture fields.

Field	Area (ha)	Mean annual application rate: Litter (Mg ha^{-1})	Total nitrogen (kg ha^{-1})	Total phosphorus (kg ha^{-1})	Land use: 2000 to 2001	2001 to 2002	2002 to 2003	2003 to 2004	2004 to 2005	2005 to 2006	2006 to 2007	2007 to 2008
Y6	6.6	0.0	146	15	Fallow	Corn	Corn	Wheat	Corn	Corn	Wheat	Corn
Y13	4.6	4.5	196	87	Fallow	Corn	Corn	Wheat	Corn	Corn	Wheat	Corn
Y10	7.5	6.7	231	130	Fallow	Corn	Corn	Wheat	Corn	Corn	Wheat	Corn
W12	4.0	9.0	245	149	Fallow	Corn	Corn	Wheat	Corn	Corn	Wheat	Corn
W13	4.6	11.2	289	200	Fallow	Corn	Corn	Wheat	Corn	Corn	Wheat	Corn
Y8	8.4	13.4	338	254	Fallow	Corn	Corn	Wheat	Corn	Corn	Wheat	Corn
SW12	1.2	0.0	0	0	Native prairie, hayed							
SW17	1.2	0.0	0	0	Coastal Bermudagrass, grazed							
W10	8.0	6.7	158	124	Coastal Bermudagrass, hayed							
Y14	2.3	13.4	335	257	Kleingrass, hayed							

that induces problematic losses of nutrients via runoff (Vories et al. 2001; Harmel et al. 2004). Although excessive off-site application will to some degree be limited due to cost constraints, the reduced regulatory oversight compared to on-site application at animal feeding operations may be problematic without effective education and outreach. In addition to these agronomic and economic factors, social barriers driven by the ever-expanding urban and rural interface and concerns related to odor problems and environmental quality tend to limit off-site application (Turnell et al. 2007).

One obstacle in achieving proper litter application management, whether on-site or off-site, is the limited availability of comprehensive, multiyear, field-scale data to guide management decisions. The lack of such data too often forces decision-makers to base policy and regulation regarding poultry litter utilization on factors other than sound science. Soil property and agricultural productivity data on long-term manure application sites are available (e.g., Kingery et al. 1994; Edmeades 2003), but data sets that include water quality effects are rare because such studies are expensive and labor intensive (Gilley and Risse 2000). One such comprehensive data set has been collected on plots in Nebraska with long-term cattle feedlot manure application (Eghball et al. 1996; Gilley et al. 1999; Eghball et al. 2002).

The present study was one component of a comprehensive, long-term study of economic, agronomic, and environmental effects of poultry litter application. The objective was to determine the runoff water quality effects of repeated annual litter application as a cropland and pasture fertilizer. The specific questions of interest were (1) do differing litter application rates create differences in runoff water quality between the fields? and (2) are there temporal trends in the effects of repeated litter application on runoff water quality?

Figure 1
Study fields (watersheds) at the USDA Agricultural Research Service Grassland, Soil and Water Research Laboratory, Riesel, Texas.

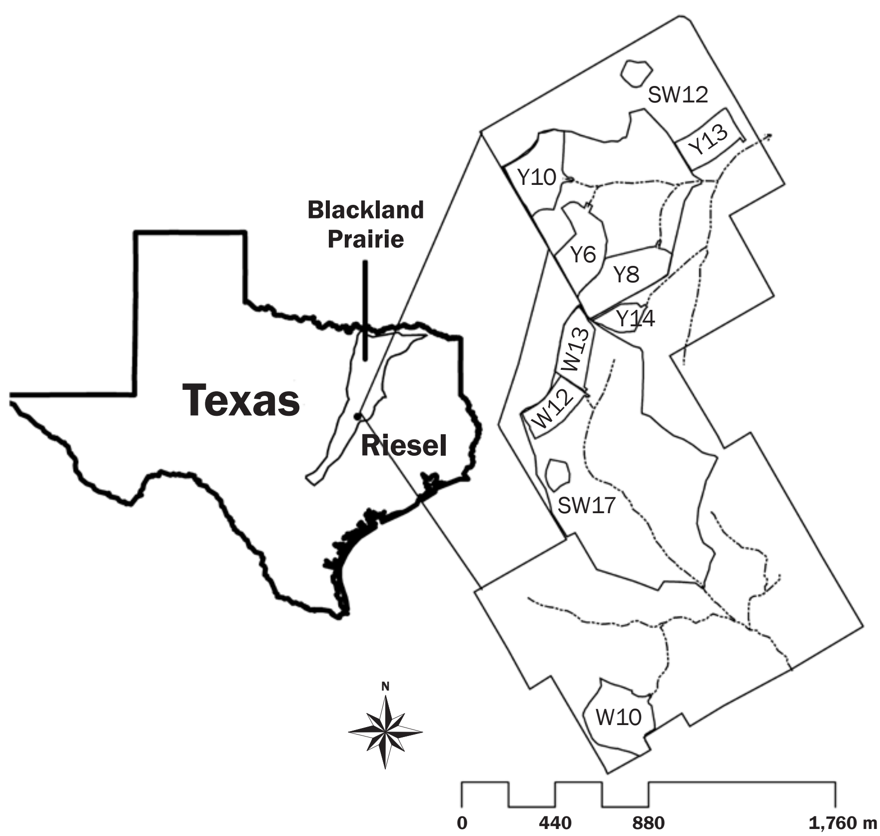


Table 2
Litter samples were collected for analysis each year immediately prior to application. The properties of the litter are presented "as-is," not on a dry-weight basis, as means with standard deviations in parentheses. The coefficients of variation (CV) for annual means are also presented.

Applied	Samples (n)	Moisture (%)	Organic C (%)	Total N (%)	Total P (%)	Water extractable nutrients NO$_3$-N (mg kg^{-1})	NH$_4$-N (mg kg^{-1})	SRP (mg kg^{-1})
July 2001	4	49.5 (15.4)	28.4 (6.3)	2.32 (0.33)	2.14 (0.12)	211 (246)	1,170 (370)	895 (238)
Sept 2002	4	9.8 (2.6)	31.2 (0.6)	3.05 (0.24)	3.47 (0.47)	857 (293)	3,775 (8)	1,234 (35)
Sept 2003	6	32.1 (4.0)	28.9 (0.3)	3.27 (0.14)	1.67 (0.23)	265 (240)	4,726 (1,160)	778 (258)
Aug 2004	4	28.0 (7.2)	28.4 (0.6)	2.27 (0.21)	1.99 (0.15)	510 (295)	2,917 (340)	799 (113)
Aug 2005	4	20.6 (4.0)	31.8 (0.7)	2.59 (0.25)	1.96 (0.16)	22 (24)	1,755 (92)	396 (23)
Aug 2006	5	14.8 (0.4)	32.3 (2.3)	2.72 (0.12)	1.41 (0.24)	7 (7)	2,870 (528)	2,953 (771)
Oct 2007	4	21.1 (1.0)	31.2 (2.1)	2.06 (0.04)	1.43 (0.10)	456 (233)	3,213 (1,416)	404 (47)
	average	25.1	30.3	2.61	2.01	333	2,918	1,065
	CV	0.52	0.06	0.17	0.35	0.91	0.41	0.83

Notes: C = carbon. N = nitrogen. P = phosphorus. NO$_3$-N = nitrate nitrogen. NH$_4$-N = ammonium nitrogen. SRP = soluble reactive phosphorus.

Materials and Methods

Site Description. In August 2000, six cropland and four pasture fields were selected as the experimental units for this study (table 1). These homogeneous land-use fields are best described as field-scale watersheds. It was at that scale that runoff volume and quality were measured. All of the study watersheds are located at the USDA Agricultural Research Service Grassland, Soil and Water Research Laboratory near Riesel, Texas (figure 1). The research site is dominated by Houston Black clay soil (fine, smectitic, thermic, udic Haplustert), which is recognized throughout the world as the classic Vertisol. These highly expansive clays, which shrink and swell with changes in moisture content, have a typical particle size distribution of 17% sand, 28% silt, and 55% clay. These soils are very slowly permeable when wet (saturated hydraulic conductivity ≈1.5 mm h^{-1} [≈0.06 in hr^{-1}]); however, preferential flow associated with soil cracks contributes to high infiltration rates when the soil is dry (Arnold et al. 2005; Allen et al. 2005).

Watershed Management. Litter application rates from 0.0 to 13.4 Mg ha^{-1} (0 to 6 ton ac^{-1}) were determined a priori and then randomly assigned to each of the six cropland watersheds (table 1). The litter rates were chosen to encompass and exceed the range of realistic application rates. The litter was obtained in the vicinity of the study site from the cleanout (either complete cleanout for multiple flocks or "cake out" from a single flock) of turkey houses. The bedding material in litter was either wood shavings or rice hulls.

Watershed Y6 served as the cropland control and as such received only inorganic fertilizer. Two pasture watersheds were chosen to receive no litter and acted as controls because of their management as native prairie (SW12) and grazed pasture (SW17). Litter rates for the other two pasture watersheds were determined a priori and then were randomly assigned (table 1). Management within each land use, cropland, and pasture was consistent to minimize confounding variations due to differing management. Only the fertilization strategy changed between treatments.

Each cropped watershed had broad-base terraces on the contour and grassed waterways at the terrace outlets. Management consisted of tillage, planting, harvest, and application of litter, supplemental N, and pesticide. In 2000 to 2001, the cropland fields were kept fallow, and no fertilizer was applied to establish baseline conditions. In 2001 to 2002, a three-year crop rotation (corn–corn–wheat) was initiated, with each field receiving a constant annual litter application rate. In the corn years, target available N rates were set at approximately 170 kg ha^{-1} (152 lb ac^{-1}) based on production recommendations by Gass (1987). It was assumed that the litter N available in the first year following application increased from 40% initially to 50% in 2004 through 2008 as soil microbial communities were enhanced (Acosta-Martinez and Harmel 2006). It was also assumed that 5% to 10% of litter N was available in the second year following application. Supplemental N was applied prior to planting if needed to reach the 170 kg ha^{-1} N target. In the wheat years, no supplemental N was added because litter supplied adequate N for wheat production (>67 kg available N ha^{-1} [>60 lb N ac^{-1}]). The cropland control field (Y6) received only inorganic N and P at rates of 170 kg N ha^{-1} (152 lb N ac^{-1}) and 14 kg P ha^{-1} (12 lb P ac^{-1}) in corn years and at 80 kg N ha^{-1} (71 lb N ac^{-1}) and 17 kg P ha^{-1} (15 lb P ac^{-1}) in wheat years. Litter was applied in the late summer each year, as soon as possible after August 1, to increase the likelihood of dry conditions and field access. Inorganic fertilizer was applied at planting or as close as possible prior to planting. Litter and inorganic fertilizers were both surface applied and incorporated within 24 hours of application. The exception occurred in 2007 to 2008 when anhydrous ammonia was injected.

Management for the four pasture fields consisted of annual litter application (surface applied), hay harvest (or grazing), and herbicide application. No fertilizer was applied to any of the pasture fields in 2000 to 2001, but a consistent litter application rate was applied to Y14 and W10 in the late summer each year from 2001 to 2008. For the pasture watersheds, no supplemental inorganic N or P was applied. The grazed pasture watershed (SW17) was opened for selective grazing at rates from 0.4 to 0.8 ha cow^{-1} (1 to 2 ac cow^{-1}) for about eight months per year.

Data collection. Seven years of runoff and water quality data were collected following litter application (August 2001 to July 2008). These August through July study years are noted as 2001 to 2002, 2002 to 2003, etc. Annual soil samples for each application field were also collected, but only soil P data are presented because of its influence on runoff P.

Litter samples were collected for analysis each year immediately prior to application (results appear in table 2). Moisture content was determined by drying at 116°C (240°F) for 24 hours. Water extractable nitrate plus nitrite nitrogen (NO$_3$+NO$_2$-N), ammonium nitrogen (NH$_4$-N), and orthophosphate phosphorus (PO_4-P) concentrations were determined with extraction methodology described in Self-Davis and Moore (2000) and subsequent colorimetric analysis. Total N and total P were determined by Kjeldahl digestion and colorimetric analysis. Organic C was determined using a total C analyzer with the primary sample ignition furnace temperature reduced to 650°C (1,200°F) (McGeehan and Naylor 1988; Schulte and Hopkins 1996).

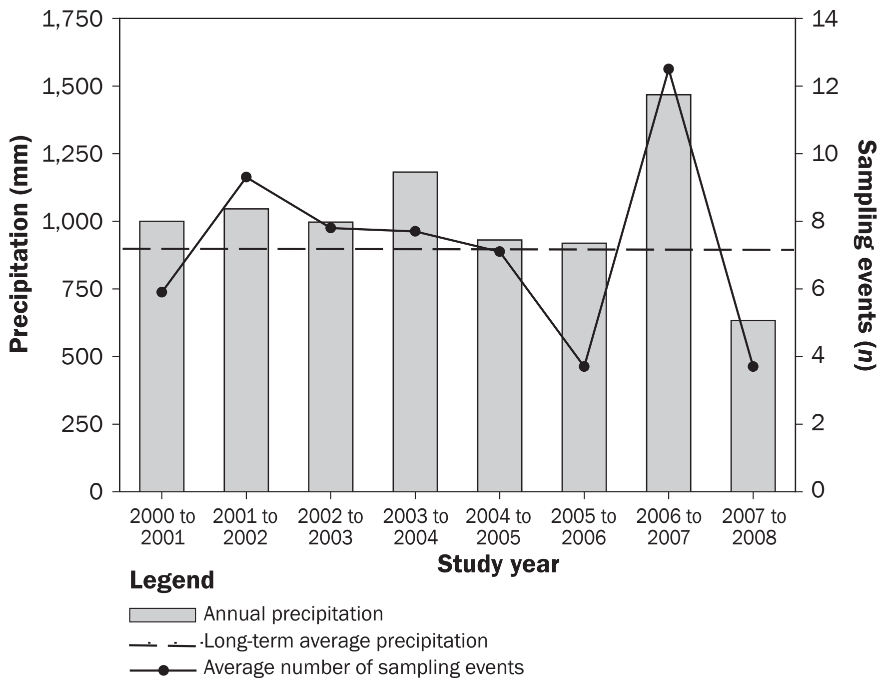
The outlet of each watershed was equipped with a flow control structure (v-notch weir or a flume and weir combination), and flow data were recorded continuously at 5- to 15-minute intervals depending on watershed size. In 2000 to 2001, mechanical Chickasha samplers were used to collect multiple water quality samples for each runoff event. Then in 2001, ISCO 6700 (ISCO Inc., Lincoln, Nebraska) automated samplers were installed to collect runoff water samples. During the eight-year period, various sampling strategies were employed; however, each was designed to sample intensively and thus minimize uncertainty based on Harmel et al. (2006a; 2006b).

At each field, rainfall depth and intensity data were collected with a Hydrologic Services tipping bucket rain gauge (Hydrologic Services PTY, Ltd., Sydney, Australia) connected to a Campbell Scientific CR10X datalogger (Campbell Scientific Inc., Logan, Utah). A standard rain gauge was also used at each field as a backup and calibration device.

Water quality samples were collected from the field within 48 hours of each runoff event and were stored at 4°C (39°F) prior to analysis. Samples were analyzed for dissolved NO_3+NO_2-N, NH_4-N, and PO_4-P concentrations using colorimetric methods (Technicon 1973a, 1973b) with a Technicon Autoanalyzer IIC (Bran-Luebbe, Roselle, Illinois) or a Flow IV Rapid Flow Analyzer (O.I. Analytical, College Station, Texas). Results for NO_3+NO_2-N are reported as nitrate nitrogen (NO_3-N) because the NO_3-N form dominates. The sediment (total settleable solids) concentration was determined by mass after settling for 3 to 5 days, decanting off a majority of the solution, and drying at 116°C (240°F) for 18 to 24 hours. The concentrations of N and P in the particulate form (total Kjeldahl nitrogen and total Kjeldahl phosphorus) were determined by a salicylic acid modification of a semimicro-Kjeldahl digestion procedure (Technicon Industrial Systems 1976). The NO_3-N and PO_4-P concentrations presented represent event mean concentrations (EMCs). The uncertainty of measured runoff concentrations was estimated with the method of Harmel et al. (2006a). Runoff loads for each runoff event were determined by multiplying concentrations by corresponding flow volumes.

Figure 2

Measured annual precipitation and average number of runoff sampling events.



Experimental Design and Statistical Analysis. Background water quality data collected prior to applying treatments indicated no inherent differences between experimental units in terms of runoff water quality within land-use categories (Harmel et al. 2004). Therefore, significant differences were confidently attributed to treatment effects.

In addition to graphical methods, one-way analysis of variance (ANOVA) followed by Tukey's pairwise mean comparison (family error rate, α = 0.05) was used to examine whether differing litter application rates created differences in mean water quality values. Linear regression analyses with an a priori α = 0.05 probability level were used to compare litter rate treatment effects and to examine possible temporal trends in the effects of repeated litter application. All statistical tests were conducted with Minitab software (Minitab 2000) according to procedures described in Helsel and Hirsch (1993) or Haan (2002).

Results and Discussion

A great deal of data has been collected to date in this study, which was designed to support long-term evaluation of repeated litter application. Thus, it was impractical to provide the complete set of data in this article. Instead, the present article focuses on summary data and selected analyses of runoff water quality. Detailed supplemental data (e.g., hydrology and water quality data for each runoff event and every management activity on each field) are available upon request. Related data and analyses are also available on initial water quality impacts (Harmel et al. 2004), on-farm agronomic and economic effects (Harmel et al. 2008a), soil microbial communities and enzyme activities (Acosta-Martinez and Harmel 2006), and soil quality (in preparation).

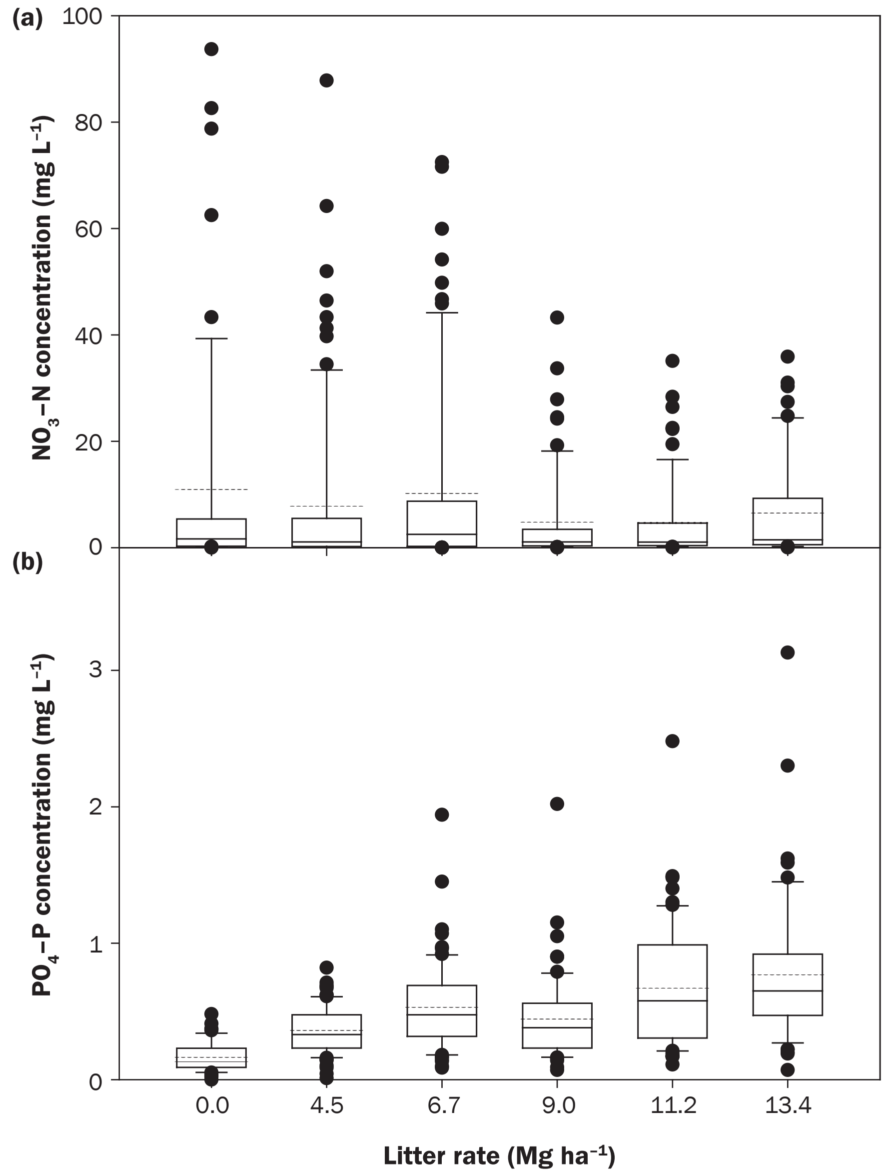
Runoff Events. During the eight-year study, water quality data were collected for 574 runoff events or approximately seven events per field per year. Seven of the eight study years experienced above-average annual precipitation based on long-term records (Harmel et al. 2003). The only dry year (2007 to 2008) produced an average of only four sampling events per field, but two fields (W10 and Y14) did not produce adequate runoff for a single sample (figure 2). To date, litter application has not noticeably affected runoff volume, which may be due to the minimal changes in soil organic C (data not reported), dominance of shrink/swell processes in Vertisol hydrology, and temporal and spatial differences in precipitation and runoff. As the project continues, potential changes in runoff due to changes in soil properties, as were reported by Gilley and Risse (2000), Vories et al. (2001), and Wortmann and Walters (2006), will be examined.

Litter Rate and Nitrate Nitrogen Concentrations in Runoff from Cropland Fields. In terms of NO_3-N concentrations in runoff, graphical methods clearly indicated the presence of treatment (litter rate) effects on cropland fields (figure 3a). Especially evident were the reduced magnitudes of extreme high NO_3-N concentrations as litter rate (and total applied N) increased. Regression analysis of maximum NO_3-N concentrations and litter rate supported this observation (p = 0.005). All of the cropland fields produced NO_3-N EMCs greater than 20 mg L^{-1}, but only the fields with more than 50% of the available N applied in inorganic forms (Y6, Y13, Y10) had any EMCs greater than 45 mg L^{-1} (figure 3a). One reason for the reduced magnitude of extreme NO_3-N concentrations was the decrease in inorganic N application corresponding to litter rate increases for corn years in which all cropland fields received the same available N rates by balancing available litter N and inorganic N. The reduced susceptibility of runoff NO_3-N from organic sources is attributed to the slow release (mineralization) of organic N and the rapid adsorption of mineralized NH_4-N by soil clay particles and organic matter compared to the immediate availability of inorganic N to plant uptake and runoff loss. The split application of litter and inorganic N also contributed to reduced runoff NO_3-N concentrations (Vories et al. 2001).

Statistical results were mixed on the effect of litter rate on typical (mean) runoff NO_3-N concentrations. No significant treatment differences in mean NO_3-N concentrations were determined by ANOVA (p = 0.067) or by regression analysis (p = 0.077), but regression analysis on individual NO_3-N concentrations did indicate a significant decreasing relationship based on litter rate (p = 0.016). The decrease in runoff NO_3-N concentrations is quite interesting since more total N was applied as litter rate increased (table 1). This result is supported by Vories et al. (2001) who also observed reduced NO_3-N concentrations and loads in runoff water from litter-fertilized cotton fields in Mississippi, even though these fields received much more total N than inorganic-fertilizer fields. Higher runoff NO_3-N concentrations from surface-applied inorganic fertilizers compared to poultry litter were also observed on pastures by Edwards and Daniel (1994) and Edwards et al. (1996).

Figure 3

Runoff event mean concentrations (EMCs) on cropland fields, (a) nitrate nitrogen (NO_3-N), (b) orthophosphate phosphorus (PO_4-P). The uncertainty for NO_3-N concentrations averaged ±24% and for PO_4-P concentrations averaged ±22%. Whereas increasing litter rate (with corresponding decreases in supplemental inorganic N) generally reduced NO_3-N concentrations on cropland fields, the opposite was true for PO_4-P concentrations.



Litter Rate and Orthophosphate Phosphorus Concentrations in Runoff from Cropland Fields. Whereas increasing litter rate (with corresponding decreases in supplemental inorganic N) generally reduced NO_3-N concentrations on cropland fields, the opposite was true for PO_4-P concentrations. Both graphical and statistical methods clearly indicated that increasing litter rate increased PO_4-P concentrations (figure 3b). This result was expected, however, because total P application increased as litter rate became greater as litter was the only fertilizer source on cropland. ANOVA followed by Tukey's test revealed many significant differences in mean concentrations corresponding to litter rate. Similarly, regression analyses indicated significant increasing relationships for treatment maximum (p = 0.001), treatment mean (p = 0.003), and individual PO_4-P EMCs (p < 0.001). Only watersheds with litter application that greatly exceeded the agronomic rate for P (≈20 to 40 kg available P ha^{-1} [≈18 to 36 lb ac^{-1}] ≈2.2 to 4.5 Mg litter ha^{-1} [≈1 to 2 ton ac^{-1}]) experienced PO_4-P concentrations in excess of 1.0 mg L^{-1} (figure 3b). Based on the present results and those of Vories et al. (2001), litter application in excess of the agronomic P rate on cropland fields increases runoff PO_4-P concentrations, and thus increases the likelihood of detrimental environmental impacts.

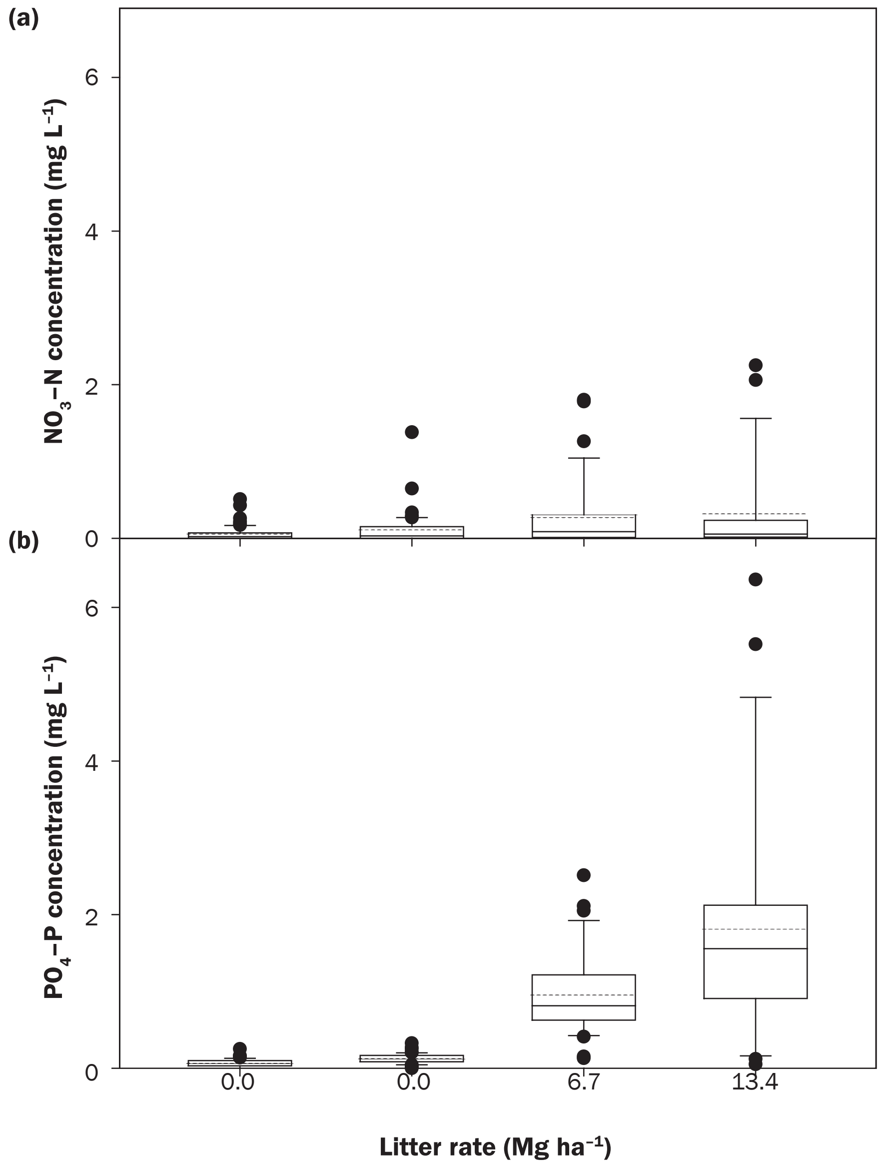
Litter Rate and Nitrate Nitrogen and Orthophosphate Phosphorus Concentrations in Runoff from Pasture Fields. Graphical and statistical analyses indicated the presence of treatment (litter rate) effects on runoff NO_3-N and PO_4-P concentrations on pasture fields (figure 4). These results were not surprising since litter application was the only fertilizer source on the pasture fields. For both NO_3-N and PO_4-P, ANOVA followed by Tukey's test indicated significant differences in mean concentrations based on litter rate. Regression analyses indicated significant increasing relationships for treatment mean (p = 0.019) and individual (p < 0.001) NO_3-N concentrations and for treatment mean (p < 0.001), treatment maximum (p = 0.01), and individual (p < 0.001) PO_4-P concentrations.

Although total N concentrations were higher than total P in the litter, runoff PO_4-P concentrations typically exceeded NO_3-N concentrations (figure 4), possibly due to higher litter soluble reactive P concentrations (table 2). Similar results were obtained on pastures with surface-applied litter by Edwards et al. (1996), who reported mean NO_3-N EMCs of 0.38 to 3.69 mg L^{-1} and mean PO_4-P EMCs of 1.64 to 2.93 mg L^{-1}. Similarly, Vervoort et al. (1998) reported NO_3-N concentrations of <1 mg L^{-1} and mean dissolved reactive P concentrations of 3.3 mg L^{-1} (~20 Mg ha^{-1} litter) and 1.2 mg L^{-1} (~10 Mg ha^{-1} litter) on pastures with surface-applied litter.

The difference between runoff concentrations on pasture and cropland fields was dramatic for NO_3-N (figure 3a, 4a). At the 6.7 Mg ha^{-1} (3 ton ac^{-1}) litter rate, for example, NO_3-N concentrations ranged from 0 to 72 mg L^{-1} on the cropland field but only from 0 to 2 mg L^{-1} on the pasture field. While the

Figure 4

Runoff event mean concentrations (EMCs) on pasture fields, (a) nitrate nitrogen (NO_3-N), (b) orthophosphate phosphorus (PO_4-P). The uncertainty for NO_3-N concentrations averaged ±57% (relatively high due to numerous very low concentrations) and for PO_4-P concentrations averaged ±30%.



6.7 Mg ha^{-1} rate cropland field did receive 1.5× more total N (table 1) than the pasture field with the same litter rate, mean runoff NO_3-N concentrations were 50× higher. This dramatic difference is speculated to have occurred because (1) cropland received inorganic N, which was readily available to runoff; (2) nutrient uptake by pasture permanent vegetation was greater; and (3) litter mineralization rates were greater on cropland fields due to litter incorporation.

The difference in runoff PO_4-P concentrations between the cropland and pasture fields was much less dramatic (figure 3b, 4b). The mean PO_4-P concentration at the 6.7 Mg ha^{-1} (3 ton ac^{-1}) litter rate was 1.0 mg L^{-1} for pasture compared to 0.5 mg L^{-1} for cropland. At the 13.4 Mg ha^{-1} (6 ton ac^{-1}) litter rate, the pasture mean was 1.8 mg L^{-1}, and the cropland mean was 0.8 mg L^{-1}. Despite tillage and vegetation differences between pasture and cropland land uses, the differences in runoff PO_4-P concentration are quite small, likely because corresponding fields both had the same, single P source (litter) and identical target P application rate

Table 3

Soil test P levels based on Mehlich 3 and H3A extractants and ICP analysis. According to the Mehlich 3-ICP test, soil test P levels increased proportionally with litter application rate.

	Cropland fields						Pasture fields			
Study year	Y6*	Y13	Y10	W12	W13	Y8	SW12	SW17	W10	Y14
	Litter rate (Mg ha^{-1})									
	0.0	4.5	6.7	9.0	11.2	13.4	0.0	0.0	6.7	13.4
	Mehlich3-ICP (mg kg^{-1})									
2000 to 2001	25	24	25	27	25	20	23	21	21	15
2001 to 2002	26	50	48	63	77	59	20	17	44	75
2002 to 2003	23	52	73	71	124	102	8	9	43	81
2003 to 2004	31	44	43	38	76	82	10	9	20	37
2004 to 2005	16	60	80	92	108	134	10	8	40	83
2005 to 2006	21	39	53	67	63	74	15	14	35	65
2006 to 2007	31	60	58	85	110	84	8	8	64	83
2007 to 2008	29	76	129	122	175	185	7	10	64	131
Average annual change	+0.4	+4.7†	+9.0	+9.7†	+12.7	+14.9†	−1.8†	−1.3	+4.7	+10.1†
Mean‡	25a	51ab	63ab	71ab	95bc	93bc	13a	12a	41b	71c
	H3A-ICP (mg kg^{-1})									
2007 to 2008	10	19	40	36	57	57	7	8	20	35

* Field descriptions appear in table 1.

† Significant at α = 0.05.

‡ Within land-use categories, mean values with the same letter are not significantly different.

(table 1). The slightly higher runoff PO_4-P concentrations from the pasture fields compared to cropland, which were also observed by Torbert et al. (2005), probably occurred because the litter remained on the pasture thatch surface, which limited soil/litter interaction and P adsorption.

Soil Extractable Phosphorus and Runoff Orthophosphate Phosphorus Concentrations. The buildup of soil P from manure and litter application is often the subject of regulatory attention related to water quality. In many south-central US states, the Mehlich 3 extractant (Mehlich 1984) has become the required test to judge compliance of confined animal feeding operation waste application permit regulations, although its design intent for acid soils is usually ignored (Somenahally et al. 2009). According to the Mehlich 3-ICP test, soil test P levels increased proportionally with litter application rate (table 3). The average annual changes in soil test P were relatively small on Y13 and W10 (+4.7 mg kg^{-1} y^{-1}), which received litter at the upper limits of the agronomic P rate but were much higher (+9.0 to +14.9 mg kg^{-1} y^{-1}) as litter rate increased further. Although mean litter N and P concentrations were similar to values for chicken litter reported by Edwards and Daniel (1992), nutrient concentrations did vary considerably during the study (table 2) and contributed to annual variability in soil test P values.

Figure 5

Runoff event mean concentrations (EMCs) of nitrate nitrogen (NO_3-N) versus time since fertilizer application for two cropland fields. The shaded areas highlight the drastic difference in NO_3-N concentrations for the inorganic only field (Y6) between the initial period following fertilizer application (>30 mg L^{-1}) and later periods (<7 mg L^{-1}).

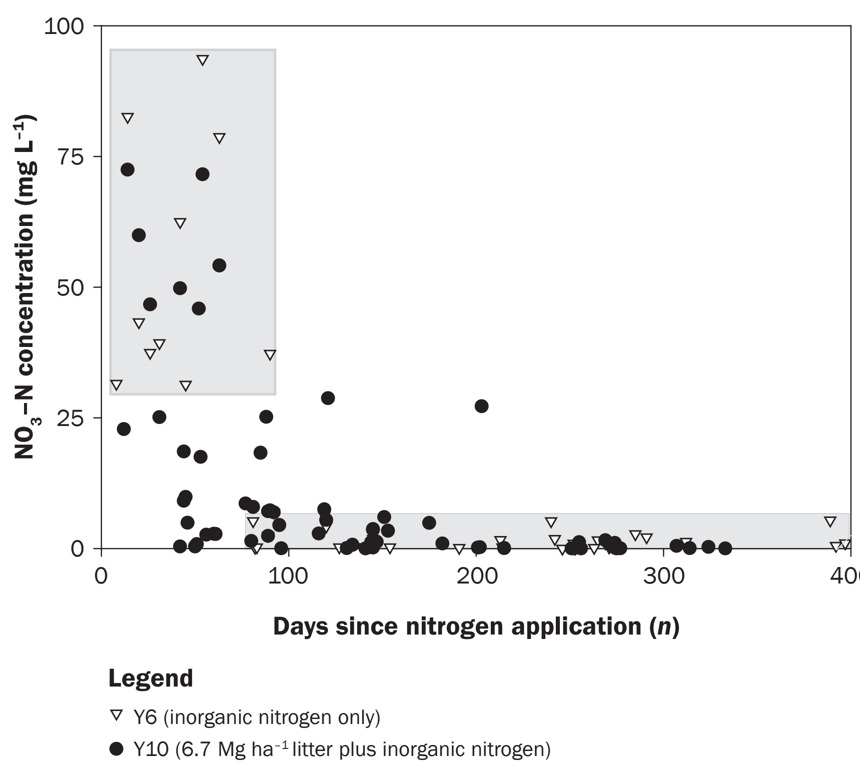
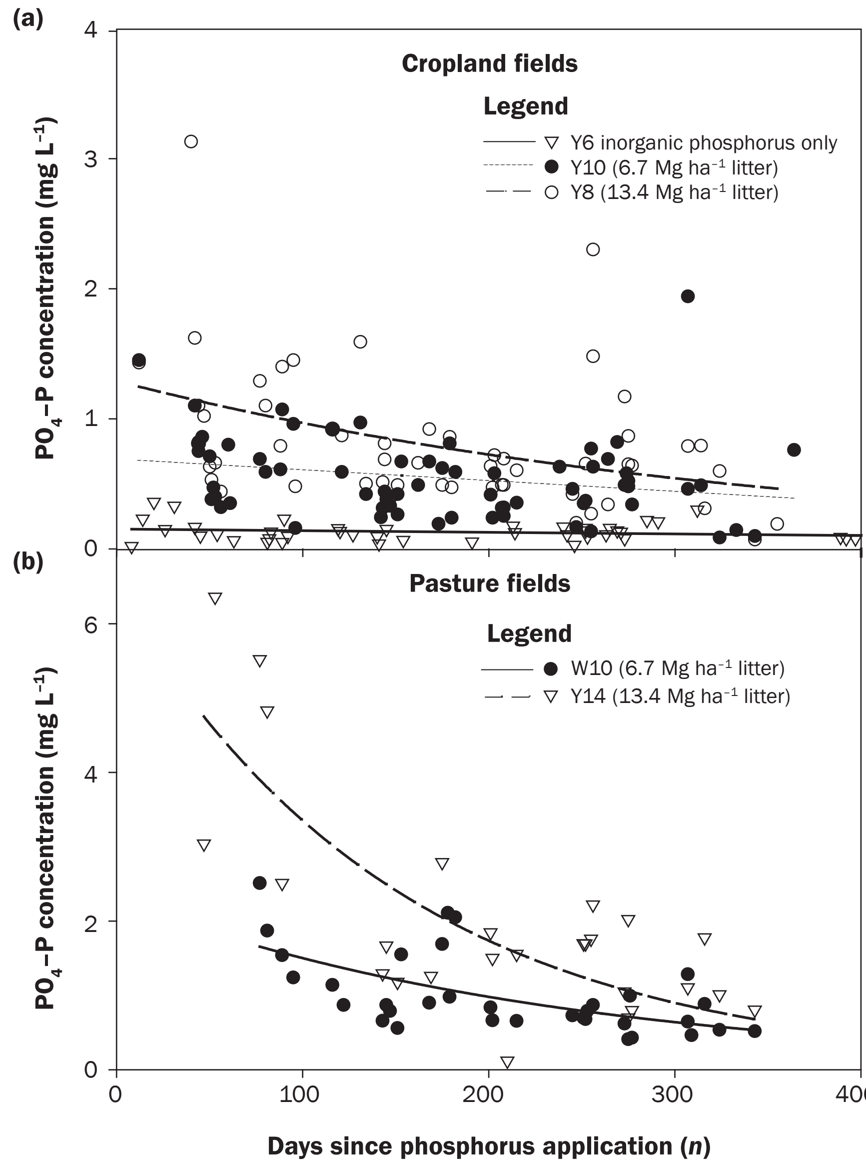


Figure 6

Runoff orthophosphate phosphorus (PO_4-P) event mean concentrations (EMCs) based on time since fertilizer application for selected: (a) cropland fields and (b) pasture fields.



An additional extractant called H3A (Haney et al. 2006), which is composed of organic root exudates, lithium citrate, and two synthetic chelators, was also used to determine soil test P levels for the 2007 to 2008 study year. On these calcareous soils with pH between 7.4 and 8.4, the strongly acidic Mehlich 3 extractant dissolves significant amounts of calcium-, iron-, and aluminum-associated P that is not available to plants or runoff. Thus, H3A extracted less P than Mehlich 3 (table 3), although the two were significantly correlated ($r^2 = 0.97$).

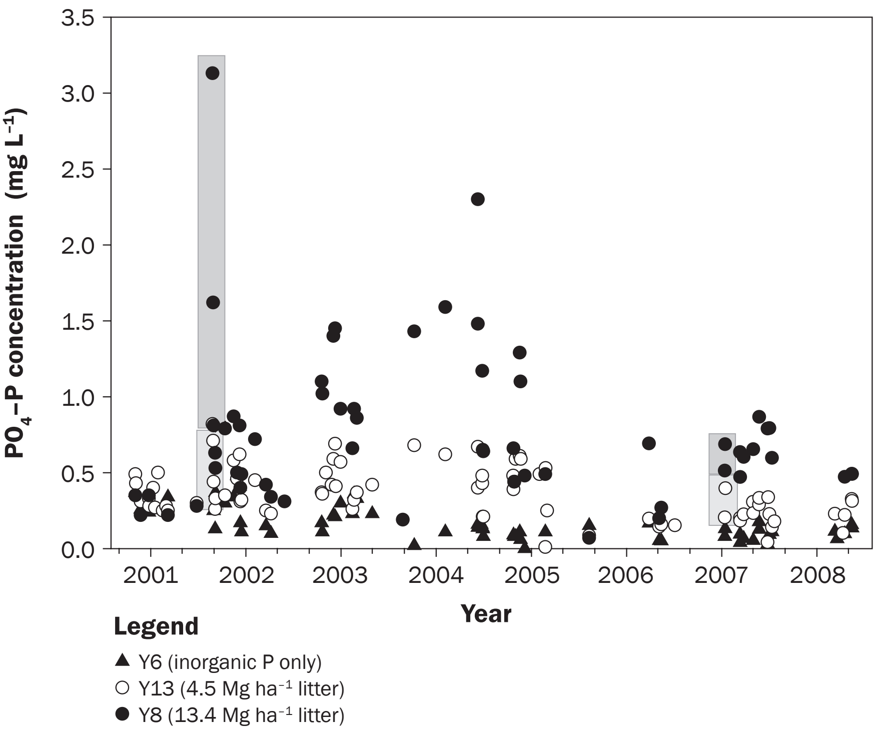
Based on 2007 to 2008 data following seven annual litter applications, runoff PO_4-P concentrations (annual mean, median, and maximum) were strongly correlated ($r^2 > 0.87$, $p \leq 0.01$) with both Mehlich 3-ICP and H3A-ICP soil test P on both land use categories. This result supports similar findings by several researchers (e.g., Sharpley et al. 1999; Kleinman et al. 2000; Torbert et al. 2002); however, correlations were much weaker when data were evaluated across years. For multiyear comparisons, differences in runoff timing, volume, and intensity affected PO_4-P concentrations, such that simple indicators alone (litter rate, soil test P) were not sufficient for accurate runoff PO_4-P prediction (DeLaune et al. 2004).

Effect of Fertilizer Application and Runoff Timing on Nitrate Nitrogen and Orthophosphate Phosphorus Concentrations. For all cropland fields, logarithmic or exponential decaying relationships were observed between runoff NO_3-N concentrations and time since fertilizer application (e.g., Y10 data in figure 5). Although intra-annual decay relationships were evident, considerable variability occurred between timing of runoff and resulting runoff NO_3-N concentrations. No runoff events occurred within one week of fertilizer application. Some very high NO_3-N EMCs occurred even 90+ days after fertilizer application, and ten events with >10 mg L^{-1} occurred after three or more months. These results indicate the contributions of both recently applied inorganic N and mineralized N (from soil and litter) on runoff NO_3-N concentrations. Another interesting aspect of these decay relationships is the contrast between the inorganic fertilizer control field (Y6), and other fields which received litter and inorganic N. Whereas NO_3-N concentrations varied considerably within the first 90 days at the litter fields, Y6 consistently produced EMCs > 30 mg L^{-1} in this initial period (figure 5). Then after about 90 days, the litter fields still produced variable NO_3-N concentrations, but Y6 never produced EMCs > 7 mg L^{-1}.

In contrast to the cropland fields, runoff from pastures with only organic fertilizer application showed no intra-annual temporal trends in NO_3-N concentrations. Similar results were also observed for grassed watersheds with inorganic fertilizer application, as Kilmer et al. (1974) reported that the highest runoff NO_3-N concentrations sometimes occurred 6 to 12 months after fertilization. In a plot-scale rainfall simulation study, Smith et al. (2007) observed increasing NO_3-N concentrations as time to the first event increased from 1 to 29 days on fescue plots fertilized with inorganic and organic fertilizers. The increases in NO_3-N concentrations during the first month after fertilization were attributed to time required for mineralization of organic N from manure and soil pools. Thus, the timing of runoff following fertilizer application can influence NO_3-N runoff, but other factors such as land use, runoff volume, mineralization of organic N, organic/inorganic N ratio, C source (bedding material), and plant uptake applied must also be considered to properly predict NO_3-N runoff.

Figure 7

Runoff event mean orthophosphate phosphorus (PO_4-P) concentractions for selected cropland fields. The shaded areas highlight the drastic differences in PO_4-P concentrations for Y13 and Y8 between the August 2001 and January 2007 events. Runoff PO_4-P was much greater in 2001 under fallow conditions with runoff occurring within six weeks of litter application, compared to 2007 with wheat cover and no runoff until more than four months after litter application.



Intra-annual curvilinear decay relationships were found for runoff PO_4-P concentrations on cropland and pasture (figure 6). Although general decay relationships were evident, considerable variability occurred between timing of runoff and resulting PO_4-P concentrations (notice the high concentrations at 250 to 300 days in figure 6a). On the cropland fields, only 4 of the 37 events with PO_4-P EMCs > 1 mg L^{-1} occurred within two weeks of fertilizer application, and 15 of these high concentration events occurred after three or more months. On the pasture fields, 24 of the 32 runoff events with PO_4-P EMCs > 1 mg L^{-1} occurred three or more months after litter application, potentially due to the relative contributions and interactions between two sources—litter P remaining on the soil surface and P within the upper soil layer. Vadas et al. (2007b) observed similar curvilinear relationships for dissolved reactive P in successive runoff events on pasture and cropland following poultry litter and dairy manure application. Smith et al. (2007) studied the time to first runoff event on fescue plots with poultry litter or inorganic fertilizer both applied at 35 kg P ha^{-1} (31 lb ac^{-1}). Soluble P concentrations were reduced from 3 mg L^{-1} to 1 mg L^{-1} when time to first runoff increased from 1 day to 29 days. Schroeder et al. (2004) conducted a similar study on fescue plots but with three rainfall scenarios: immediately after application, after 30 days with no rainfall, and after 30 days with weekly, short-duration rainfall events. In these simulated events, exponential decay in PO_4-P concentrations over time was observed, but the decay was much more uniform than observed at the field-scale in the present study (figure 6) or in Pierson et al. (2001). Schroeder et al. (2004) attributed the considerable variability of runoff P concentrations at the field-scale compared to plot studies to variable source area hydrology and to temporal and spatial variations in soil microbial activity, a process that is too often underappreciated in fertilizer studies. The recently published model of Vadas et al. (2007a) considers this variability by incorporating temporal dynamics in manure properties and storm hydrology when predicting dissolved P loss in runoff from surface-applied animal manures. Other models that use simple decay relationships, as observed in figure 6, may not capture variability in manure P runoff as well (Schroeder et al. 2004; Hively et al. 2005).

Long-term Trends in Nitrogen and Phosphorus Loss. As noted in the previous description of intra-annual N and P loss patterns, the dynamic interactions of transport factors (runoff and erosion) and source factors (fertilizer application and residual soil nutrients)—as presented in P Index discussions (e.g., DeLaune et al. 2004)—also affected potential long-term trends. One example of the effect of these dynamic interactions was the difference in runoff PO_4-P concentrations for August 2001 and January 2007, which were periods with similar successive large rainfall events (figure 7). Runoff PO_4-P was much greater in 2001 under fallow conditions with runoff occurring within six weeks of litter application, compared to 2007 with wheat cover and no runoff until more than four months after litter application.

These dynamic interactions between nutrient transport and source factors produced considerable temporal variability and overwhelmed other trends, such as dramatic increases in soil test P on high litter rate fields (table 3). No significant trends were observed in annual particulate, dissolved, or total P or N loads for cropland or pasture fields based on regression of annual loads and study year (tables 4, 5). Similarly, runoff P concentrations did not significantly increase according to regression analysis of EMCs and storm date (e.g., figure 7). In fact, PO_4-P concentrations actually decreased ($p < 0.01$) on the three lowest litter rate cropland fields (Y6, Y13, and Y10) but exhibited no significant change at the highest litter rates. No trends were observed in runoff NO_3-N concentrations on cropland, and the only significant changes for pasture occurred in the control fields that received no fertilizer. The NO_3-N concentrations increased ($p = 0.039$) at SW12, and PO_4-P concentrations decreased ($p = 0.023$) at SW17. These results emphasize the importance of considering intra-annual interactions of transport and source factors for accurate predictions of N and P runoff.

Summary and Conclusions

Seven years of repeated annual litter application produced several significant runoff water quality differences based on litter rate and land use but did not affect runoff volumes. On cropland, increasing litter rates (with corresponding decreases in supplemental

Table 4
Annual total, dissolved, and sediment-bound N loads for cropland and pasture fields.*

Study year	Cropland fields Y6†	Y13	Y10	W12	W13	Y8	Pasture fields SW12	SW17	W10	Y14
	Total nitrogen (kg ha^{-1})									
2000 to 2001	1.2	5.7	2.2	4.3	2.6	1.9	na‡	na	0.1	0.0
2001 to 2002	22.5	50.5	41.3	28.0	18.3	28.6	0.6	8.5	0.3	0.1
2002 to 2003	42.4	32.6	52.8	18.7	27.5	24.1	0.7	0.4	0.2	0.1
2003 to 2004	16.0	6.6	11.2	6.6	10.6	5.4	1.5	0.6	0.5	0.6
2004 to 2005	6.7	13.5	14.1	6.1	15.8	16.4	0.6	0.6	1.4	2.3
2005 to 2006	14.8	18.9	17.1	12.0	8.1	12.7	0.4	0.5	0.1	0.3
2006 to 2007	2.9	6.1	5.5	5.7	9.0	5.4	1.3	1.2	0.9	2.0
2007 to 2008	8.2	15.7	21.7	5.2	4.7	3.5	0.2	0.8	0.0	0.0
	Dissolved nitrogen (kg ha^{-1})									
2000 to 2001	0.3	2.1	0.7	1.1	0.9	0.6	na	na	0.1	0.0
2001 to 2002	14.7	28.5	34.7	13.0	7.2	16.1	0.1	0.1	0.2	0.0
2002 to 2003	38.8	29.3	50.3	16.0	24.7	21.7	0.2	0.2	0.1	0.1
2003 to 2004	14.7	5.7	9.9	5.6	8.7	4.4	0.1	0.1	0.3	0.4
2004 to 2005	3.7	10.1	11.7	4.7	13.1	13.7	0.1	0.1	1.1	2.0
2005 to 2006	12.1	14.8	14.1	8.4	5.6	10.2	0.0	0.1	0.1	0.2
2006 to 2007	1.1	1.3	1.8	3.8	7.3	3.5	0.4	0.4	0.5	0.9
2007 to 2008	6.6	12.6	16.1	2.0	1.5	1.1	0.2	0.2	0.0	0.0
	Particulate nitrogen (kg ha^{-1})									
2000 to 2001	0.9	3.5	1.6	3.2	1.8	1.2	na	na	0.0	0.0
2001 to 2002	7.9	22.0	6.6	14.9	11.1	12.5	0.5	8.4	0.1	0.1
2002 to 2003	3.6	3.3	2.5	2.7	2.8	2.4	0.5	0.2	0.1	0.0
2003 to 2004	1.3	0.8	1.3	1.0	2.0	1.0	1.4	0.5	0.3	0.2
2004 to 2005	2.9	3.4	2.4	1.3	2.7	2.7	0.5	0.5	0.3	0.3
2005 to 2006	2.7	4.2	3.0	3.6	2.5	2.5	0.4	0.4	0.0	0.1
2006 to 2007	1.8	4.8	3.7	1.9	1.8	1.9	0.9	0.8	0.4	1.0
2007 to 2008	1.6	3.1	5.6	3.2	3.2	2.4	0.1	0.7	0.0	0.0

* Differences due to rounding.

† Field descriptions appear in table 1.

‡ A complete set of storm samples was not collected; therefore, annual loads were not determined.

inorganic N) increased PO_4-P concentrations but reduced extreme high NO_3-N concentrations. On pasture, increasing litter rates increased NO_3-N and PO_4-P concentrations in runoff, since litter was the only fertilizer source. Following seven annual litter applications, annual PO_4-P concentrations were strongly correlated with both Mehlich 3-ICP and H3A-ICP soil test P levels on both land uses. Within each year, runoff NO_3-N and PO_4-P concentrations generally decreased as time since fertilizer application increased, but this effect was quite variable due to the dynamic interactions of rainfall, runoff, vegetation condition, soil nutrient levels, and fertilizer application. These interactions also limited consistent, long-term trends in N and P runoff in spite of soil P buildup, which was dramatic at annual litter rates greater than 6.7 Mg ha^{-1} (3 ton ac^{-1}).

Practical Implications. In addition to issues of scientific interest, the present study produced several practical outcomes. First, combining inorganic and organic fertilizers can be an effective fertilization strategy on farms and ranches (off-site of animal production operations). With this strategy, organic fertilizers are applied at the P rate and thus provide necessary P and micronutrients as well as organic matter and some N. Supplemental inorganic fertilizers are then applied to meet the remaining N requirement. For the cropland conditions studied, the ideal long-term litter application rate was shown to be 2.2 to 4.5 Mg ha^{-1} (1 to 2 ton ac^{-1}). Application rates in this range minimized water quality concerns in terms of NO_3-N and PO_4-P runoff compared to inorganic fertilization. For cropland, this environmentally optimal range is also economically optimal in terms of maximizing profit (Harmel et al. 2008a). The ideal long-term annual litter rate for pasture is anticipated to be 4.5 to 6.7 Mg ha^{-1} (2 to 3 ton ac^{-1}), which is slightly higher than for cropland due to increased nutrient uptake potential, increased infiltration, and reduced erosion (although no economic analyses were conducted on pastures).

Second, application of fertilizer (organic or inorganic) during forecasts of heavy rainfall increases the potential for considerable runoff nutrient losses (and wasted inputs) and thus should be avoided. Although it is widely recognized that the greatest N and P concentrations typically occur in the first runoff event following fertilizer application (e.g., Vories et al. 2001; Kleinman and Sharpley 2003; Vadas et al. 2007b), runoff occurring weeks and even months after fertilizer application can still produce high N and P concentrations (e.g., Kilmer et al. 1974; Pierson et al. 2001; Schroeder et al. 2004).

Table 5
Annual total, dissolved, and sediment-bound P loads for cropland and pasture fields.*

Study year	Cropland fields						Pasture fields			
	Y6†	Y13	Y10	W12	W13	Y8	SW12	SW17	W10	Y14
	Total phosphorus (kg ha^{-1})									
2000 to 2001	0.4	1.7	0.6	1.5	0.7	0.5	na‡	na	0.0	0.0
2001 to 2002	3.2	10.6	3.4	7.9	5.9	6.6	0.1	1.9	0.6	0.4
2002 to 2003	1.7	1.9	2.8	1.6	3.1	2.4	0.2	0.3	1.2	0.6
2003 to 2004	0.5	1.2	1.9	1.3	2.8	2.5	0.2	0.2	1.1	2.3
2004 to 2005	1.2	2.3	1.9	1.5	2.9	2.5	0.2	0.3	4.0	10.5
2005 to 2006	0.8	1.2	1.0	1.4	1.1	0.8	0.1	0.1	0.2	0.6
2006 to 2007	0.8	3.4	2.9	1.9	3.4	3.7	0.4	0.5	2.8	7.0
2007 to 2008	0.4	0.8	1.2	0.7	0.8	0.7	0.1	0.1	0.0	0.0
	Dissolved phosphorus (kg ha^{-1})									
2000 to 2001	0.3	1.1	0.4	1.2	0.6	0.3	na	na	0.0	0.0
2001 to 2002	0.4	1.3	1.4	1.2	1.2	1.4	0.1	0.2	0.5	0.4
2002 to 2003	0.5	0.9	2.1	0.8	2.1	1.6	0.1	0.3	1.1	0.6
2003 to 2004	0.2	1.0	1.7	1.1	2.4	2.2	0.1	0.2	1.0	2.3
2004 to 2005	0.2	1.1	1.1	1.0	1.9	1.6	0.1	0.2	3.8	10.2
2005 to 2006	0.1	0.2	0.2	0.3	0.3	0.2	0.0	0.0	0.2	0.6
2006 to 2007	0.4	1.3	2.2	1.5	2.9	3.1	0.3	0.4	2.6	6.5
2007 to 2008	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.0	0.0
	Particulate phosphorus (kg ha^{-1})									
2000 to 2001	0.2	0.6	0.3	0.3	0.2	0.2	na	na	0.0	0.0
2001 to 2002	2.8	9.3	1.9	6.7	4.7	5.1	0.0	1.7	0.0	0.0
2002 to 2003	1.3	1.0	0.7	0.9	1.0	0.8	0.1	0.0	0.0	0.0
2003 to 2004	0.3	0.2	0.2	0.2	0.4	0.3	0.2	0.1	0.1	0.0
2004 to 2005	1.0	1.2	0.8	0.5	0.9	0.9	0.1	0.1	0.2	0.3
2005 to 2006	0.7	1.1	0.7	1.1	0.8	0.6	0.1	0.1	0.0	0.0
2006 to 2007	0.4	2.1	0.7	0.4	0.5	0.6	0.1	0.1	0.2	0.5
2007 to 2008	0.4	0.6	1.0	0.6	0.6	0.5	0.0	0.0	0.0	0.0

* Differences due to rounding.
† Field descriptions appear in table 1.
‡ A complete set of storm samples was not collected; therefore, annual loads were not determined.

Management of fertilizer timing cannot prevent this. In other words, the management of fertilizer timing should not be solely relied upon to reduce N and P loss in runoff (Hart et al. 2004).

Third, the tradeoff between reduced N and P loss potential and increased application costs with split fertilizer application should be carefully considered in fertilizer management. Because of water quality concerns, double litter rates applied every other year are not recommended except for the 2.2 Mg ha^{-1} (1 ton ac^{-1}) litter rate. At that average annual rate, applying litter at 4.5 Mg ha^{-1} (2 ton ac^{-1}) every other year is anticipated to have little adverse soil and water quality impact.

Fourth, high concentrations of NO_3-N and PO_4-P in runoff can occur on well-managed fields. This observation presents serious regulatory implications, especially in light of a recent suit against US Environmental Protection Agency regarding regulation of nutrient runoff in Florida (Skoloff 2008). Determining appropriate edge-of-field water quality standards to regulate diffuse rural runoff is extremely challenging since most regulators and scientists do not know what environmentally significant and reasonably attainable nutrient concentrations are at that scale. It is not appropriate to simply "push downstream standards upstream" and apply them at the field-scale given drastically different dilution, transformation, and channel contribution mechanisms. If overly strict edge-of-field standards are established, then Dougherty et al. (2008) and results of the present research both suggest that attainment may be impossible even when proper management is implemented. Thus, when and if, edge-of-field water quality standards are established, they should be based on data collected at the appropriate scale, such as inventoried in Harmel et al. (2008b). In the meantime, farmers and ranchers should actively pursue best management practices to reduce nutrient losses and keep valuable fertilizer on their fields.

Finally, a change is needed in the animal industry mindset regarding manure and litter. Viewing these by-products as, "resources to be marketed regionally and not wastes to be disposed of locally," (Janzen et al. 1999) would tend to increase off-site application and thus mitigate environmental problems created by overapplication on "waste" application fields. Within this paradigm, litters and manures represent revenue opportunities, instead of costs to animal producers, and provide attractive fertilizer alternatives to farmers and ranchers faced with increasing input costs.

Acknowledgments

The authors would like to recognize the dedicated and talented farm staff and hydrologic technicians at Riesel. They deserve much credit for their valuable contribution to this long-term project. They are Lynn Grote, Steve Grote, Gary Hoeft, and Larry Koester. Funding for this project has been provided by the Texas State Soil and Water Conservation Board, US Environmental Protection Agency, and USDA Agricultural Research Service. Dr. Gobbler Inc. also deserves credit for their efforts in supplying the litter and their willingness to apply it as directed by research needs.

Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.

References

Acosta-Martinez, V., and R.D. Harmel. 2006. Soil microbial communities and enzyme activities under various poultry litter application rates. Journal of Environmental Quality 35(4):1309-1318.

Allen, P.M., R.D. Harmel, J. Arnold, B. Plant, J. Yeldermann, and K. King. 2005. Field data and flow system response in clay (Vertisol) shale terrain, north central Texas, USA. Hydrological Processes 19(14):2719-2736.

Arnold, J.G., K.N. Potter, K.W. King, and P.M. Allen. 2005. Estimation of soil cracking and the effect on surface runoff in a Texas Blackland Prairie watershed. Hydrological Processes 19(3):589-603.

Bekele, A., A.M.S. McFarland, and A.J. Whisenant. 2006. Impacts of a manure composting program on stream water quality. Transactions of the American Society of Agricultural Engineers 49(2):389-400.

DeLaune, P.B., B.E. Haggard, T.C. Daniel, I. Chaubey, and M.J. Cochran. 2006. The Eucha/Spavinaw phosphorus index: A court mandated index for litter management. Journal of Soil and Water Conservation 61(2):96-105.

DeLaune, P.B., P.A. Moore, D.K. Carman, A.N. Shapley, B.E. Haggard, and T.C. Daniel. 2004. Development of a phosphorus index for pastures fertilized with poultry litter - Factors affecting phosphorus runoff. Journal of Environmental Quality 33(6):2183-2191.

Dougherty, W.J., P.J. Nicholls, P.J. Milham, E.J. Havilah, and R.A. Lawrie. 2008. Phosphorus fertilizer and grazing management effects on phosphorus in runoff from dairy pastures. Journal of Environmental Quality 37(2):417-428.

Edmeades, D.C. 2003. The long-term effects of manures and fertilisers on soil productivity and quality: A review. Nutrient Cycling in Agroecosystems 66(2):165-180.

Edwards, D.R., and T.C. Daniel. 1992. Environmental impacts of on-farm poultry waste disposal-A review. Bioresource Technology 41(1):9-33.

Edwards, D.R., and T.C. Daniel. 1994. A comparison of runoff quality effects of organic and inorganic fertilizers applied to fescuegrass plots. Water Resources Bulletin 30(1):35-41.

Edwards, D.R., T.C. Daniel, J.F. Murdoch, and P.A. Moore, Jr. 1996. Quality of runoff from four northwest Arkansas pasture fields treated with organic and inorganic fertilizer. Transactions of the American Society of Agricultural Engineers 39(5):1689-1696.

Eghball, B., G.D. Binford, and D.D. Baltensperger. 1996. Phosphorus movement and adsorption in a soil receiving long-term manure and fertilizer application. Journal of Environmental Quality 25(6):1339-1343.

Eghball, B., J.E. Gilley, D.D. Baltensperger, and J.M. Blumenthal. 2002. Long-term manure and fertilizer application effects on phosphorus and nitrogen in runoff. Transactions of the American Society of Agricultural Engineers 45(3):687-694.

Gass, W.B. 1987. Plant soil and water testing laboratory recommendations. College Station, TX: Texas Agricultural Extension Service.

Gilley, J.E., B. Eghball, J.M. Blumenthal, and D.D. Baltensperger. 1999. Runoff and erosion from interrill areas as affected by the application of manure. Transactions of the American Society of Agricultural Engineers 42(4):975-980.

Gilley, J.E., and L.M. Risse. 2000. Runoff and soil loss as affected by the application of manure. Transactions of the American Society of Agricultural Engineers 43(6):1583-1588.

Haan, C.T. 2002. Statistical Methods in Hydrology, 2nd edition. Ames, IA: The Iowa State Press.

Haggard, B.E., P.A. Moore Jr., I. Chaubey, and E.H. Stanley. 2003. Nitrogen and phosphorus concentrations and export from an Ozark Plateau catchment in the United States. Biosystems Engineering 86(1):75-85.

Haney, R.L., E.B. Haney, L.R. Hossner, and J.G. Arnold. 2006. Development of a new soil extractant for simultaneous phosphorus, ammonium, and nitrate analysis. Communications in Soil Science and Plant Analysis 37(11/12):1511-1523.

Harmel, R.D., R.J. Cooper, R.M. Slade, R.L. Haney, and J.G. Arnold. 2006a. Cumulative uncertainty in measured streamflow and water quality data for small watersheds. Transactions of the American Society of Agricultural and Biological Engineers 49(3):689-701.

Harmel, R.D., B. Harmel, and M.C. Patterson. 2008a. On-farm agro-economic effects of fertilizing cropland with poultry litter. Journal of Applied Poultry Research 17:545-555.

Harmel, R.D., K.W. King, B.E. Haggard, D.G. Wren, and J.M. Sheridan. 2006b. Practical guidance for discharge and water quality data collection on small watersheds. Transactions of the American Society of Agricultural and Biological Engineers 49(4):937-948.

Harmel, R.D., K.W. King, C.W. Richardson, and J.R. Williams. 2003. Long-term precipitation analyses for the central Texas Blackland Prairie. Transactions of the American Society of Agricultural Engineers 46(5):1381-1388.

Harmel, R.D., S.S. Qian, K.H. Reckhow, and P. Casebolt. 2008b. The MANAGE database: Nutrient load and site characteristic updates and runoff concentration data. Journal of Environmental Quality 37(6):2403-2406.

Harmel, R.D., H.A. Torbert, B.E. Haggard, R. Haney, and M. Dozier. 2004. Water quality impacts of converting to a poultry litter fertilization strategy. Journal of Environmental Quality 33(6):2229-2242.

Hart, M.R., B.F. Quin, and M.L. Nguyen. 2004. Phosphorus runoff from agricultural land and direct fertilizer effects: A review. Journal of Environmental Quality 33(6):1954-1972.

Helsel, D.R., and R.M. Hirsch. 1993. Statistical methods in water resources. New York: Elsevier.

Hively, W.D., P. Gerard-Marchant, and T.S. Steenhuis. 2005. Distributed hydrological modeling of total dissolved phosphorus transport in an agricultural landscape, part II: Dissolved phosphorus transport. Hydrology and Earth Systems Science: Discussion 2:1581-1612.

Jacks, G.V. 1954. Soil. London: Nelson and Sons.

Janzen, R.A., W.B. McGill, J.J. Leonard, and S.R. Jeffrey. 1999. Manure as a resource - Ecological and economic consideration in balance. Transactions of the American Society of Agricultural Engineers 42(5):1261-1273.

Kilmer, V.J., J.W. Gilliam, J.F. Lutz, R.T. Joyce, and C.D. Eklund. 1974. Nutrient losses from fertilized grassed watersheds in western North Carolina. Journal of Environmental Quality 3(3):214-219.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins 1994. Impact of long-term application of broiler litter on environmentally related soil properties. Journal of Environmental Quality 23(1):139-147.

Kleinman, P.J.A., R.B. Bryant, W.S. Reid, A.N. Sharpley, and D. Pimentel. 2000. Using soil phosphorus behavior to identify environmental thresholds. Soil Science 165(12):943-950.

Kleinman, P.J.A., and A.N. Sharpley. 2003. Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. Journal of Environmental Quality 32(3):1072-1081.

McGeehan, S.L., and D.V. Naylor. 1988. Automated instrumental analysis of carbon and nitrogen in plant and soil samples. Communications in Soil Science and Plant Analysis 19(4):493-505.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of the Mehlich 2 extractant. Communications in Soil Science and Plant Analysis 15(12):1409-1416.

Minitab. 2000. MINITAB 12. State College, PA; Minitab Inc.

Motavalli, P.P., S.H. Anderson, and P. Pengthamkeerati. 2003. Surface compaction and poultry litter effects on corn growth, nitrogen availability, and physical properties of a claypan soil. Field Crops Research 84(3):303-318.

Pierson, S.T., M.L. Cabrera, G.K. Evanylou, H.H. Kuykendall, C.S. Hoveland, M.A. McCann, and L.T. West. 2001.

Phosphorus and ammonium concentrations in surface runoff from grasslands fertilized with broiler litter. Journal of Environmental Quality 30(5):1784-1789.

Schroeder, P.D., D.E. Radcliffe, and M.L. Cabrera. 2004. Rainfall timing and poultry litter application rate effects on phosphorus loss in surface runoff. Journal of Environmental Quality 33(6):2201-2209.

Schulte, E.E., and B.G. Hopkins. 1996. Estimation of soil organic matter by weight loss-on-ignition. *In* Soil Organic Matter: Analysis and Interpretation, ed. F.R. Magdoff, M.A. Tabatabai, and E.A. Hanlon, Jr., 21-32. Special publication No. 46. Madison, WI: Soil Science Society of America.

Self-Davis, M.L., and P.A. Moore, Jr. 2000. Determining water soluble phosphorus in animal manure. *In* Methods of Phosphorus Analysis in Soils, Sediments, Residuals and Waters, ed. G.M. Pierzynski. Southern Cooperative Series Bulletin No. 396. Raleigh, NC: North Carolina State University.

Sharpley, A.N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. 2003. Agricultural Phosphorus and Eutrophication, 2nd Ed. USDA Agricultural Research Service Publication ARS–149.

Sharpley, A.N., W.J. Gburek, G. Folmar, and H.B. Pionke. 1999. Sources of phosphorus exported from an agricultural watershed in Pennsylvania. Agricultural Water Management 41(2):77-89.

Skoloff, B. 2008. Environmentalists sue EPA for cleaner water rules. Associated Press.

Smith, D.R., P.R. Owens, A.B. Leytem, and E.A. Warnemuende. 2007. Nutrient losses from manure and fertilizer applications as impacted by time to first runoff event. Environmental Pollution 147(1):131-137.

Somenahally, A., D.C. Weindorf, L. Darilek, J.P. Muir, R. Wittie, C. Thompson, and C.L.S. Morgan. 2009. Spatial variability of soil test phosphorus in manure-amended soils on three dairy farms in North Central Texas. Journal of Soil and Water Conservation 64(2):89-97.

Stockdale, E.A., M.A. Shepherd, S. Fortune, and S.P. Cuttle. 2002. Soil fertility in organic farming systems - fundamentally different? Soil Use and Management 18(s1):301-308.

Technicon Industrial Systems. 1973a. Nitrate and Nitrite in Water and Waste Water. Industrial Method no. 100-70w. Roselle, IL: Bran-Luebbe.

Technicon Industrial Systems. 1973b. Ammonia in Water and Waste Water. Industrial Method no. 98-70w. Bran-Luebbe, Roselle, IL.

Technicon Industrial Systems. 1976. Individual/simultaneous determination of nitrogen and/or phosphorus in BD acid digest. Industrial method no. 344-74a. Roselle, IL: Bran-Luebbe.

Torbert, H.A., T.C. Daniel, J.L. Lemunyon, and R.M. Jones. 2002. Relationship of soil test phosphorus and sampling depth to runoff phosphorus in calcareous and noncalcareous soils. Journal of Environmental Quality 31(4):1380-1387.

Torbert, H.A., R.D. Harmel, K.N. Potter, and M. Dozier. 2005. Evaluation of some phosphorus index criteria in cultivated agriculture in clay soils. Journal of Soil and Water Conservation 60(1):21-29.

Turnell, J.R., R.D. Faulkner, and G.N. Hinch. 2007. Recent advances in Australian broiler litter utilisation. World's Poultry Science Journal 63(2):223-231.

USDA and USEPA (Environmental Protection Agency). 1999. Unified National Strategy for Animal Feeding Operations, March 9, 1999.

Vadas, P.A., W.J. Gburek, A.N. Sharpley, P.J.A. Kleinman, P.A. Moore Jr., M.L. Cabrera, and R.D. Harmel. 2007a. A model for phosphorus transformation and runoff loss for surface-applied manures. Journal of Environmental Quality 36(1):324-332.

Vadas, P.A., R.D. Harmel, and P.J.A. Kleinman. 2007b. Transformations of soil and manure phosphorus after surface application of manure to field plots. Nutrient Cycling in Agroecosystems 77(1):83-99.

Vervoort, R.W., D.E. Radcliffe, M.L. Cabrera, and M. Latimore, Jr. 1998. Field-scale nitrogen and phosphorus losses from hayfields receiving fresh and composted broiler litter. Journal of Environmental Quality 27(5):1246-1254.

Vories, E.D., T.A. Costello, and R.E. Glover. 2001. Runoff from cotton fields fertilized with poultry litter. Transactions of the American Society of Agricultural Engineers 44(6):1495-1502.

Wortmann, C.S., and D.T. Walters. 2006. Phosphorus runoff during four years following composted manure application. Journal of Environmental Quality 35(2):651-657.