

# Effect of direct incorporation of poultry litter on phosphorus leaching from coastal plain soils

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**Abstract:** Management of poultry litter on the Delmarva Peninsula is critical to reducing phosphorus losses to the Chesapeake Bay. New poultry litter incorporation technologies have shown promise at reducing phosphorus losses, but their effectiveness has not been tested in this environmentally sensitive region. This study evaluates subsurface leaching losses of three litter application methods, including surface broadcast, surface broadcast with disking, and subsurface litter incorporation with a novel litter incorporator developed by the USDA Agricultural Research Service. Cube-shaped soil lysimeters ( $61 \times 61 \times 61$  cm [ $24 \times 24 \times 24$  in]) were extracted from high phosphorus (P) (Mehlich-3 P is greater than  $500 \text{ mg kg}^{-1}$ ) agricultural soils on the University of Maryland Eastern Shore Research Farm near Princess Anne, Maryland, and were subjected to two rainfall simulation events that were separated by 11 semiweekly soaking-type irrigation events. The average cumulative total phosphorus loss was highest for the subsurface litter incorporation method ( $0.48 \text{ kg ha}^{-1}$  [ $0.43 \text{ lb ac}^{-1}$ ]) and was lowest for the no litter control ( $0.19 \text{ kg ha}^{-1}$  [ $0.17 \text{ lb ac}^{-1}$ ]). Particulate P loss among manure treatments ranged from 58% to 64% of total P loss. Total phosphorus losses were strongly correlated to total phosphorus concentration in the leachate (coefficient of determination [ $r^2$ ]  $\geq 0.84$ ), indicating availability of P in applied litter to be the primary control of P in leachate. Soil properties also impacted P leaching losses, with the soils possessing a higher sand content and having a shallower depth to the sandy subsoil, yielding higher cumulative total P losses ( $0.64 \text{ kg ha}^{-1}$  [ $0.57 \text{ lb ac}^{-1}$ ]). Although the subsurface litter incorporator increased total P leaching losses, a concern on the Delmarva Peninsula, opportunity exists to modify the subsurface incorporator design using zone tillage, potentially reducing the leaching losses.

**Key words:** leaching—lysimeter—phosphorus—poultry litter

**Management of poultry litter is a key water quality concern on the Delmarva Peninsula, which abuts the Chesapeake Bay.** In 2009, the poultry industry on Delmarva produced over 568 million broilers (Delmarva Poultry Industry 2009). These birds would be expected to produce approximately 713,000 Mg (786,000 tn) of litter (Patterson et al. 1998). The Chesapeake Bay is threatened by accelerated eutrophication caused by anthropogenic nitrogen and phosphorus (P) loadings, with agriculture considered a primary contributor of both nutrients. To help improve bay water quality, states within the Chesapeake Bay watershed have implemented nutrient management strategies aimed at curtailing nutrient transfers from agricultural lands to the bay and its tribu-

utaries (Boesch et al. 2001). Implementation of best management practices for nutrients has been the hallmark of agricultural nutrient management activities, recognizing that the unique physiographic conditions of the Delmarva Peninsula can complicate the adoption of nutrient management best management practices from other areas (Sims and Kleinman 2005).

The Delmarva Peninsula is located within the Atlantic Coastal Plain province characterized by poorly drained soils that are typically underlain by sandy marine deposits (Matthews and Hall 1966). To improve soil drainage on the peninsula, an extensive network of surface ditches has been developed, but these ditches also serve as direct conduits for nutrient from fields to Delmarva tribu-

taries (Mozaffari and Sims 1994). Indeed, large losses of P have been documented in effluent from ditches draining fields receiving poultry litter, with the majority of that P transferred by subsurface flow (Kleinman et al. 2007). As a result, best management practices focused on controlling surface runoff and associated nutrient transfers may not be appropriate for the physiographic conditions of the Delmarva Peninsula.

Application of manure to no-till/reduced-till soils is an area of continued management interest. Various forms of reduced tillage are widespread on the Delmarva Peninsula, and no-till soil management is rapidly expanding in soybean (*Glycine max* L.) and corn (*Zea mays* L.) production. Traditionally, manure is broadcast to no-till soils, but repeated application of manure to the soil surface can increase manure nutrient losses in runoff due to direct transfers of manure nutrients to surface runoff (Daverede et al. 2004) or subsurface transfer along intact soil macropores (Butler and Coale 2005) and can exacerbate losses of ammonia nitrogen to the atmosphere (Malgeryd 1998). Incorporation of manure by tillage has been recommended on a periodic basis to address nutrient stratification concerns (Sharpley 2003) and can break up macropores that serve as preferential flow paths (Shipitalo and Gibbs 2000) but is anathema to no-till objectives. Manure injection, long practiced with liquid manures to directly incorporate manure, has not been feasible with dry manures and has had reports of conflicting research results from the stand point of exacerbating subsurface losses (Weslien et al. 1998).

Little information exists on the potential effect of manure application method on P leaching through soils. Because the transport

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of P through soils is seen to be a macropore phenomenon, any placement of manure in direct contact with macropores would be expected to exacerbate P leaching. Shipitalo and Gibbs (2000) demonstrated that injected swine slurry was directly transferred to a tile drain via macropores, specifically earthworm burrows. However, it is unclear whether leachate from dry manures would behave similarly.

Until recently, the incorporation of poultry litter into soil has only been possible by cultivating soils that had received surface application of litter. Under simulated conditions, Pote et al. (2003) demonstrated that the placement of poultry litter into an 8 cm (3 in) deep furrow lowered P loss in runoff water from pasture by an average of 84% relative to surface-applied litter. A novel poultry litter incorporator developed by USDA Agricultural Research Service's (ARS) National Soil Dynamics Laboratory in Auburn, Alabama, bands poultry litter into a shallow furrow, which is sealed with closing wheels (Warren et al. 2008). This prototype incorporator has shown promise in a variety of cropping systems, from no-till cotton and corn to pasture, with a demonstrated ability to improve nitrogen use efficiency of applied litter and to decrease P and nitrogen losses in surface runoff (Sistani et al. 2009; Tewolde et al. 2009). To date, no alternative technologies for subsurface application of litters are commercially available.

This study seeks to assess the effect of a novel technology for direct incorporation of poultry litter into no-till soils on nutrient losses in leachate. Specifically, we use monolith lysimeters to compare phosphorus losses in leachate from an unmanured control and three litter application treatments: surface application of litter; surface application of litter followed by disking; and subsurface incorporation of litter.

## Materials and Methods

**Study Site.** The study site is the Research and Teaching Farm of the University of Maryland Eastern Shore in Princess Anne, Maryland (38°12'22"N, 75°40'35"W). The farm was a commercial broiler operation for roughly 30 years before it was purchased by the University of Maryland Eastern Shore in 1997. The farm was being managed in a corn–small grain–soybean rotation. Additional background on management and nutrient flows on the farm can be found in Kleinman et al. (2007) and Schmidt et al.

**Table 1**

Soil properties obtained from samples taken adjacent to each of the 20 lysimeters.

Depth increment (cm)	Property				
	Bulk density (Mg m <sup>-3</sup> )	WEP (mg kg <sup>-1</sup> )	M-3 P (mg kg <sup>-1</sup> )	NO <sub>3</sub> -N (mg kg <sup>-1</sup> )	NH <sub>4</sub> -N (mg kg <sup>-1</sup> )
0 to 5	na	57.0	542	1.41	3.88
5 to 15	0.9*	53.3	559	0.89	1.93
15 to 30	1.2	33.1	264	0.33	0.65
30 to 45	1.5	12.2	94	0.31	0.56
45 to 60	1.5	4.7	40	0.33	0.61

Notes: na = not applicable. WEP = water-extractable phosphorus. M-3 P = Mehlich-3 phosphorus. NO<sub>3</sub>-N = nitrate nitrogen. NH<sub>4</sub>-N = ammonium nitrogen.

\* Bulk density shown for 5 to 15 cm depth increment represents bulk density for 0 to 15 cm depth increment.

(2007). Soils on the farm include the poorly drained Othello series (fine-silty, mixed, active, mesic Typic Endoaquult) and well-drained Matapeake series (fine-silty, mixed, semiactive, mesic Typic Hapludult), which are derived from colian materials underlain by coarser marine sediments (Matthews and Hall 1966). Soils are enriched with nutrients due to the long history of receiving poultry litter in excess of crop requirement (table 1) (Kleinman et al. 2007).

The farm is extensively drained with open ditches. Monitoring of these ditches since 2000 shows that approximately 45% of precipitation is exported in ditch flow from fields, with more than half of ditch effluent likely derived from groundwater (Kleinman et al. 2007). Most of the nutrients in ditch flow derive from subsurface transport. Annual rainfall at the farm averages 1,110 mm (44 in). Average annual temperature is 13°C (55°F), with a monthly average high of 25°C (78°F) in July and a low of 3°C (37°F) in January.

**Litter Application Trials.** A trial was established to compare the USDA ARS poultry litter incorporator with two other commonly available litter application options. Four litter application treatments were applied to a 5 × 20 m (16 × 66 ft) area on a shoulder position (slope ≈ 1% to 3%) in a field that had been under no-till cultivation for three years and had been planted in corn the previous year (2007). Five treatment replications were arranged spatially, blocked by soil characteristics to enable post-hoc assessment of variability related to soil physical properties. The four experimental manure treatments were an unamended control, broadcast on the surface without incorporation, broadcast on the surface with disk incorporation into the soil to a depth of 8 to 10 cm (3 to 4 in), and direct subsurface incorporation with the

**Table 2**

Properties of poultry manure used in study.

Property	Value
Dry matter	78.7%
Total nitrogen	45.6 g kg <sup>-1</sup>
Total phosphorus	19.3 g kg <sup>-1</sup>
WEP	7.2 g kg <sup>-1</sup>

Notes: Values are on a dry matter basis. WEP = water-extractable phosphorus. The solution:solid ratio for the WEP test was 200:1.

USDA ARS implement (Warren et al. 2008) into a trench at a depth of 4 to 8 cm (1.5 to 3 in). The subsurface incorporation manure treatment consisted of applying the litter in shallow trenches at 76 cm (30 in) intervals, using a four-shank tractor-mounted experimental poultry litter subsurface incorporation implement. Each litter band extended from about 4 to 8 cm (1.5 to 3 in) beneath the soil surface and had a width of about 4 cm (1.5 in). In a single pass of the implement, the trencher component formed the full 4 cm (1.5 in) width of the trench and held the trench open while the implement deposited litter into the trench. Trailing press wheels closed the trench.

A total of twenty 61 × 61 × 61 cm (24 × 24 × 24 in) monolith lysimeters were collected from the 5 × 20 m (16 × 66 ft) plot area. Ten lysimeters were collected one to two days prior to litter application, five replicates each for the unamended control and broadcast treatments. The poultry litter used for the experiment came from the University of Maryland Eastern Shore broiler houses and had been stored in an open-sided shed; the properties of this litter are listed in table 2. On April 16, 2008, litter was broadcast at a rate of 6.7 Mg ha<sup>-1</sup> (3 tn ac<sup>-1</sup>) and was disked

into the ground with a tandem disk harrow pulled by a farm tractor over the areas identified for the broadcast then disked treatment.

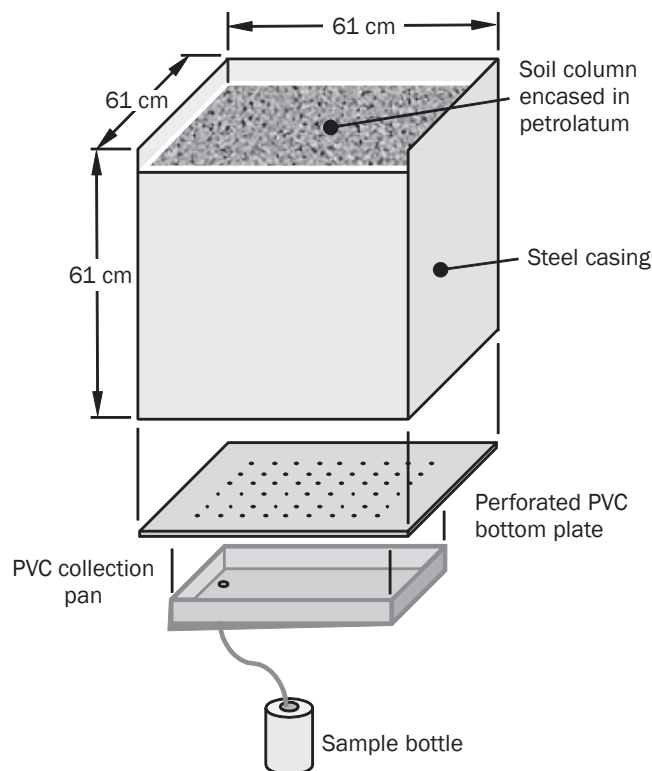
The broadcast then disked manure treatment lysimeters were extracted immediately, and the subsequent holes were filled in. On the same day, litter was evenly spread by hand over the surface of the broadcast treatment lysimeters. Then litter was ground through a hammer mill so as to readily pass through the USDA ARS machine and was incorporated into the ground over the areas identified for the subsurface incorporation treatment, and the remaining five replicate lysimeters were excavated.

**Lysimeter Collection.** The lysimeters followed the design of Feyereisen and Folmar (2009), as depicted in figure 1. A  $61 \times 61 \times 61$  cm ( $24 \times 24 \times 24$  in) steel cube, open at the bottom and top with walls 0.6 cm (0.25 in) thick, was placed over the sampling area before being driven into the soil with a 1.1 Mg (1.25 tn) drop weight. The interior walls of each cube were lined with 1.3 cm (0.5 in) thick polyvinyl chloride (PVC) plates that were later removed and replaced with liquefied petrolatum (petroleum jelly) to securely separate the soil from the painted steel walls and to suppress sidewall by-pass flow. A steel cutting head was placed on the bottom of the steel cube to aid insertion, protect the bottom edge of the PVC liners, and push excess soil to the outside of the lysimeter casing during this process. The drop weight was not allowed to contact the soil surface, so the steel cubes extended approximately 4 cm (1.6 in) above the surface of the soil columns. Columns were removed by excavating the soil adjacent to the submerged cube and then tilting the cube to cleanly break contact between the soil column and the underlying subsoil. Profiles of the soil abutting each lysimeter at time of extraction were described for all lysimeters, soil moisture measurements were recorded, and bulk samples from the center of major horizons were collected for analysis.

While at the field site, bottoms were installed onto each lysimeter by inverting the soil-filled steel cube in a specially designed rotational device to expose the bottom of the soil column. First, any space between the bottom of the soil and the bottom of the steel cube was filled with washed sand. Then, a bottom consisting of nylon geotextile secured to a 1.3 cm (0.5 in) PVC plate with 72 holes of 0.6 cm (0.25 in) diameter

**Figure 1**

Diagram of the laboratory-scale lysimeter system designed for simultaneous investigation of overland flow and subsurface leaching.



Note : PVC = polyvinyl chloride.

was attached (figure 1). Lysimeters were then returned to the upright position. Poultry litter was applied to the broadcast manure treatment lysimeters after they were returned upright. The lysimeters were covered and transported 400 km (250 mi) with the PVC spacers intact to an insulated, indoor facility at the USDA ARS Pasture Systems and Watershed Management Research Unit field station in Klingerstown, Pennsylvania, where they were inspected and further prepared for rainfall simulation experiments per the methods of Feyereisen and Folmar (2009). Each lysimeter was shimmed to create an average soil slope of 3% and was situated such that the corn row from the previous year's crop aligned with the middle of the lysimeter, perpendicular to the slope. For each subsurface incorporation lysimeter, the centerline of the subsurface band of litter was 5 to 10 cm (2 to 4 in) upslope of and parallel to the corn row.

**Rainfall Simulation and Leaching Study.** The precipitation regime chosen for this

study simulated a field situation wherein poultry litter would be applied in late February, would be subjected to a runoff event shortly thereafter, would receive the 30-year average precipitation for Princess Anne, Maryland, for the months of March and April, and then would be subjected to a second runoff event, prior to the establishment of a summer crop. In order to simulate this field situation, which is conducive to leaching and runoff losses, there was no cover crop or row crop actively growing on the lysimeters during the experiment. In following the chosen precipitation regime, the lysimeters were subjected to an initial rainfall simulation event (May 1, 2008), 11 semiweekly irrigation events, and a second rainfall simulation event (June 12, 2008).

Twenty-four and 18 hours prior to the first rainfall simulation event, additions of water of 2 cm (0.8 in) and 1 cm (0.4 in) depths, respectively, were made by uniform sprinkling such that runoff did not occur, in order to wet the soil and litter and equilibrate the samples' surfaces, which had been relatively dry since

lysimeter excavation. Soil moisture content of the surface on all lysimeters was measured prior to both rainfall simulations. Prior to each of the semiweekly irrigation events, the surface soil moisture content of four randomly selected lysimeters was measured; a different set of four lysimeters was measured prior to each irrigation event, and after all had been measured, the rotation was iterated.

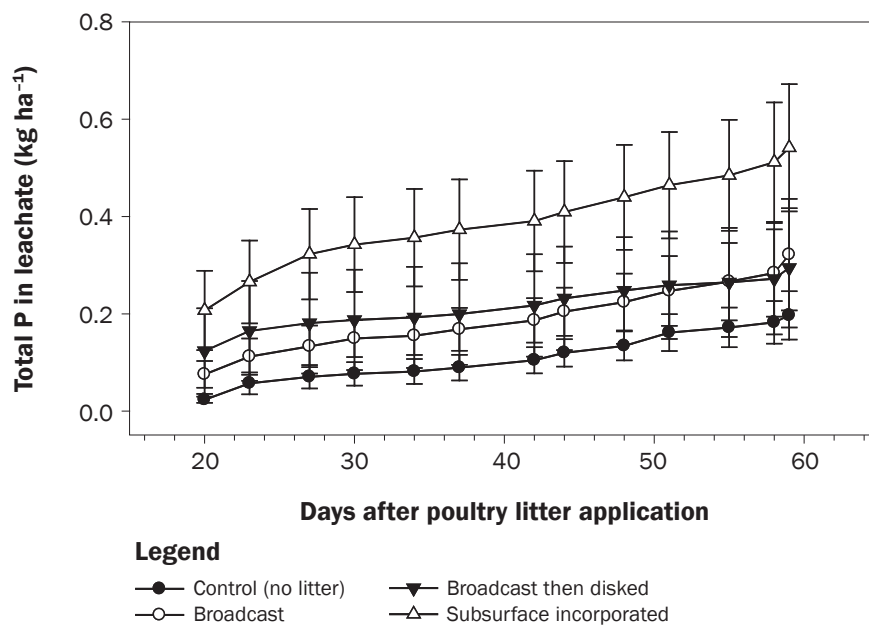
The rainfall simulations were conducted using a modified protocol of Sharpley et al. (2001). A single nozzle (Spraying Systems Co. FullJet 1/2 HH SS 30WSQ) was situated on a frame at a height of approximately 3.05 m (10 ft) above the soil surface of the lysimeters. The simulation duration was 60 minutes at an average intensity of  $6.06 \text{ cm h}^{-1}$  ( $2.38 \text{ in hr}^{-1}$ ). The uniformity coefficient was 0.85, determined by measuring rainfall in  $61 \times 61 \text{ cm}$  ( $24 \times 24 \text{ in}$ ) pans spaced to represent the soil surfaces of the lysimeters. Lysimeters were grouped by blocks of four for the simulation test, with each of the four treatments represented in a block and each block assigned by like soil characteristics (texture of the argillic layer and depth to the underlying sandy subsoil). After onset of runoff, water samples were collected at five-minute intervals. Leachate samples were collected during and after the rainfall event until drainage ceased. Between the rainfall simulations, 11 irrigation events were conducted by sprinkling a water depth of 1.5 cm (0.59 in) onto each lysimeter without creating any runoff. Leachate was collected from each of these irrigation events, weighed, and sampled for laboratory analysis.

Leachate samples were refrigerated immediately after collection until they were analyzed for total P, total dissolved P, and dissolved reactive P. For total P and total dissolved P, unfiltered and filtered ( $0.45 \mu\text{m}$  [ $1.77 \times 10^{-5} \text{ in}$ ]) leachate samples, respectively, were digested by alkaline persulfate method (Patton and Kryskalla 2003) with P concentration determined colorimetrically by a modified method of Murphy and Riley (1962), with  $\lambda = 712 \text{ nm}$  ( $2.80 \times 10^{-5} \text{ in}$ ). For dissolved reactive P, filtered samples were analyzed colorimetrically. Particulate P was calculated as the difference between total P and total dissolved P; dissolved organic P was determined by the difference between total dissolved P and dissolved reactive P.

Losses from the subsurface incorporation manure treatment were corrected for the mismatch of the lysimeter width (61 cm [24

**Figure 2**

Cumulative total phosphorus (P) leachate loss by manure treatment. The first and last events were rainfall simulations; the other events were irrigations. Each half bar represents one standard error.



in]) and the row spacing (76 cm [30 in]) by accounting for leaching losses expected from the additional 15 cm (6 in) of unamended soil found in the field but not collected in the lysimeter. The corrected losses averaged 9.6% less than the measured losses from the subsurface incorporation manure treatment. Once a loss was determined for each lysimeter in the subsurface incorporation manure treatment, the average leachate concentration for each analyte was determined by multiplying the loss (in units of  $\text{kg ha}^{-1}$ ) times the surface area of the lysimeter and dividing by the leachate depth for that lysimeter, where leachate depth was calculated as the volume of leachate collected divided by the horizontal area of the soil in the lysimeter.

**Data Analysis.** Leachate data were analyzed to assess trends related to litter application method and edaphic variability. Analysis of variance was performed using the general linear models procedure with SAS version 9.1 (SAS Institute Inc. 2002). Tukey's honestly significant difference test was employed to make pairwise comparisons and to separate treatment means. We compared the soil block means using an approximate procedure to determine an F-statistic and p-value as discussed in Montgomery (1997). The approximate F-statistic used,  $F_0$ , was the ratio of the mean square of the soil blocks

to the mean square error. Given the inexact nature of the  $F_0$  test, we did not perform a means separation test. Relationships between variables were quantified by least squares regression with Microsoft Office Excel 2003 software (Microsoft 2003). Treatment differences discussed in the text were significant at  $\alpha \leq 0.10$ .

## Results and Discussion

### Trends Related to Manure Treatments.

Total P losses varied widely among manure treatments with differences seen early in the experiment and carrying through to cumulative effects (figure 2). The cumulative total P leachate loss for the subsurface incorporation manure treatment was  $0.48 \text{ kg ha}^{-1}$  ( $0.43 \text{ lb ac}^{-1}$ ), roughly two and one-half times that of the control ( $0.19 \text{ kg ha}^{-1}$  [ $0.17 \text{ lb ac}^{-1}$ ]), with the broadcast and broadcast then disked manure treatments falling in between the two (figure 2). The loss difference between the control and subsurface incorporation manure treatments was significant; however, because of high variability for the disturbed-surface manure treatments (broadcast then disked and subsurface incorporated) the differences between each of the broadcast and broadcast then disked manure treatments and the subsurface incorporation manure treatment were not significant, even though the mean losses were



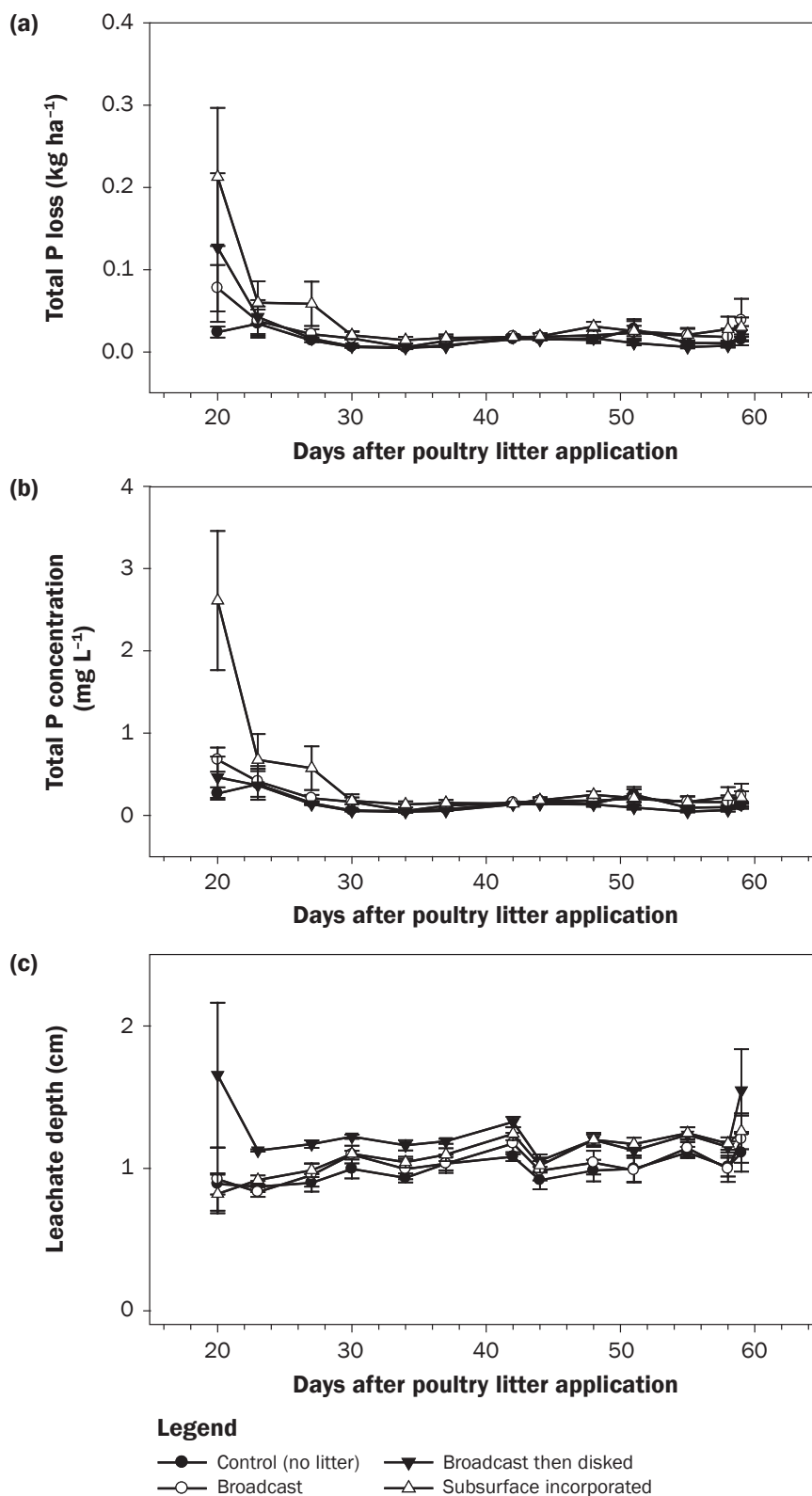
67% and 60% of the subsurface incorporation manure treatment mean loss, respectively. For the control treatment, cumulative total P losses of individual replicate values ranged from 0.11 to 0.38 kg ha<sup>-1</sup> (0.10 to 0.34 lb ac<sup>-1</sup>). The range in values across individual lysimeters for each of the three manured treatments was more than double that of the control treatment: 0.15 to 0.79, 0.12 to 0.79, and 0.18 to 0.72 kg ha<sup>-1</sup> (0.13 to 0.70, 0.11 to 0.70, and 0.16 to 0.64 lb ac<sup>-1</sup>) for the broadcast, broadcast then disked, and subsurface incorporation manure treatments.

Temporal trends in cumulative P losses among treatments varied. For two of the three manured treatments, the cumulative total P loss increased throughout the experiment with respect to the control treatment. The cumulative loss difference between the control and subsurface incorporation treatments increased steadily from 0.15 to 0.28 kg ha<sup>-1</sup> (0.13 to 0.25 lb ac<sup>-1</sup>) from the first through the last rainfall event, caused by the rapid release of manure-related P (Preedy et al. 2001). Between the control and broadcast treatments, the cumulative loss difference increased from 0.05 to 0.13 kg ha<sup>-1</sup> (0.04 to 0.12 lb ac<sup>-1</sup>) throughout the experiment, again presumably indicating the transfer of manure-related P down through the soil profile. In contrast, the cumulative loss difference between the control and broadcast then disked treatments remained at 0.10 kg ha<sup>-1</sup> (0.09 lb ac<sup>-1</sup>) at the beginning and end of the experiment. Although the broadcast manure treatment mean loss was initially less than the broadcast then disked manure treatment, it increased at a faster rate as the experiment continued until it crossed over the broadcast then disked manure treatment by the end of the experiment. This shift in relative cumulative losses was associated with higher mean concentrations of P in leachate from the broadcast manure treatment (figure 3), discussed in greater detail below.

The cumulative total P losses seen in this experiment were high relative to reported values, likely because the baseline, i.e., control, was elevated. The Mehlich-3 P concentrations in these soils exceeded 500 mg kg<sup>-1</sup> with an associated water extractable P greater than 50 mg kg<sup>-1</sup>, resulting in large leachate P losses from the control (0.19 kg ha<sup>-1</sup> [0.17 lb ac<sup>-1</sup>]) associated with soil P desorption alone. Indeed, the differences in total P loss between the control and broadcast or broadcast then disked manure treatments may have been significant if there

**Figure 3**

Individual event (a) total phosphorus (P) loss via leaching, (b) total P leachate concentration, and (c) leachate depth by manure treatment. The first and last events were rainfall simulations; the other events were irrigations. Each half bar represents one standard error.



**Table 3**Coefficients of determination ( $r^2$ ) for the relationships of total phosphorus (P) loss versus concentration by event and total P loss versus leachate depth by event.

Manure treatment	n	Total P loss versus concentration		Total P loss versus leachate depth	
		$r^2$	p-value	$r^2$	p-value
Control	65	0.94	<0.01	0.04	0.11
Broadcast	65	0.91	<0.01	0.24	<0.01
Broadcast then disked	65	0.84	<0.01	0.59	<0.01
Subsurface incorporation	65	0.85	<0.01	0.04	0.12
All data points	260	0.70	<0.01	0.16	<0.01

Notes: n = number of event data pairs used in the regression analysis.

had been lower initial soil P values. The losses observed in the current study were consistent with previous findings from the site, which estimated that subsurface flow contributed at least 2 kg ha<sup>-1</sup> yr<sup>-1</sup> (1.8 lb ac<sup>-1</sup> yr<sup>-1</sup>) of total P to the loss in nearby ditches (Kleinman et al. 2007).

Total P losses were driven largely by trends in the concentration of leachate (figure 3). Regression analysis of event total P losses revealed that coefficient of determination ( $r^2$ ) values for the total P losses versus concentration relationships were  $\geq 0.84$  for all four treatments (table 3). The relationships between P loss and leachate depth were generally weak. The strong relationship of P loss and concentration points to the dominant control of P sources on leachate P losses from these lysimeters. These sources included both the litter and the soil. The only strong relationship between total P losses and leachate depth was for the broadcast then disked manure treatment, for which the  $r^2$  was 0.59.

Differences in leachate P concentration among treatments were greatest in the first events after litter application, with the largest difference between the subsurface incorporation and the control treatments (figure 3b). After the third irrigation event, the total P leachate concentration differences between treatments and between samples within each treatment narrowed. This was consistent with the depletion of a P source to leachate, in this case applied litter, and has been observed elsewhere in leaching studies where livestock manure was applied (e.g., van Es et al. 2004). After the fifth irrigation event, the differences in concentrations between treatments were not significant as variability increased among samples for the broadcast and subsurface incorporation manure treatments. Concentrations of leachate total P observed after the fifth irrigation event (0.05 to 0.25 mg L<sup>-1</sup>) fall within the range for groundwater P concentration reported by

Vadas et al. (2007) obtained from wells on the University of Maryland Eastern Shore research farm and were comparable to the range of concentrations in studies reviewed by Sims et al. (1998).

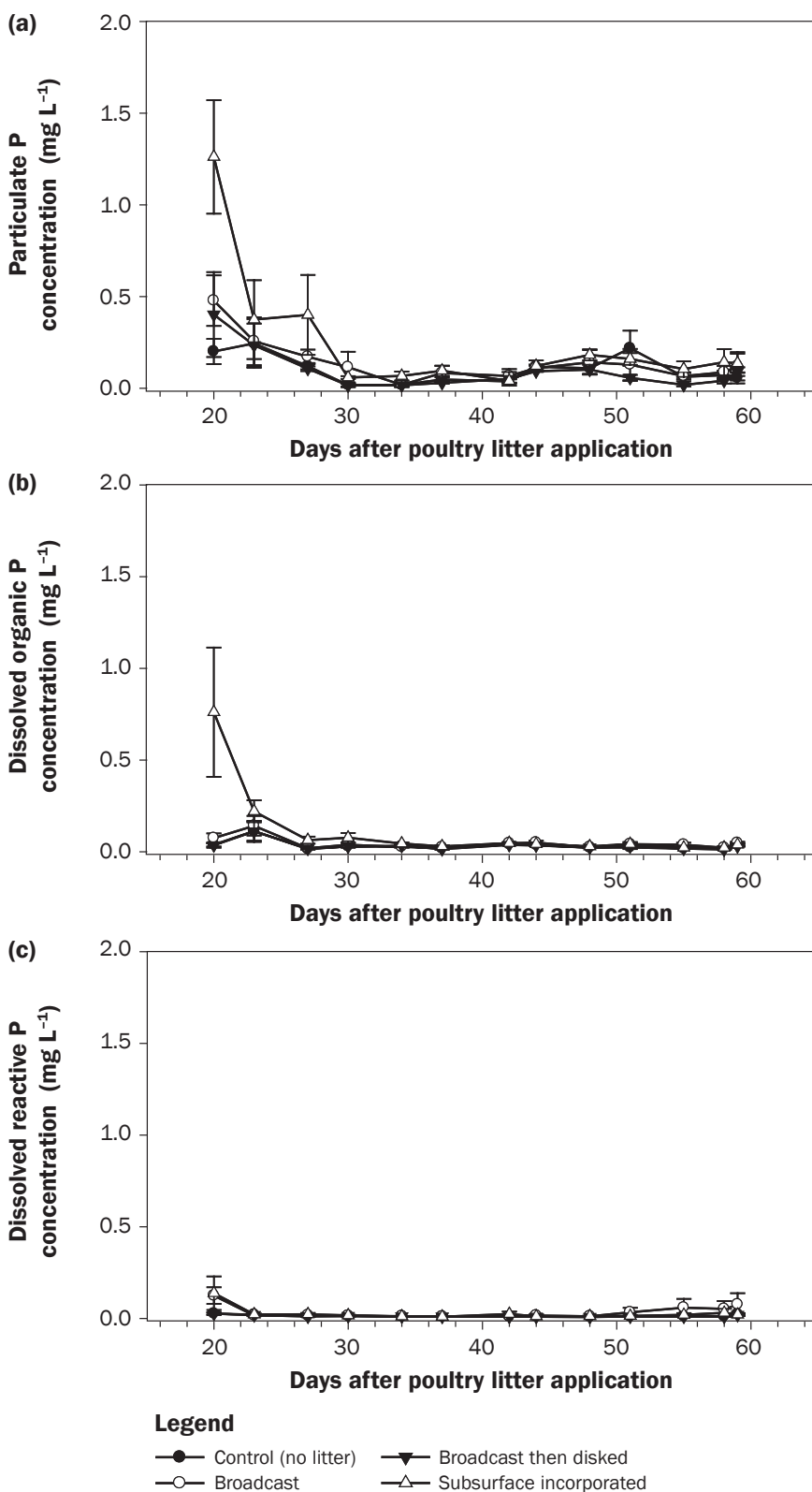
Temporal trends in leachate depth reflected differences among manure treatments as well as differences among rainfall simulation and irrigation events (figure 3c). Significant differences in leachate depths were observed in all irrigation events and the second rainfall simulation event but not in the initial rainfall simulation event where variability was highest. The two litter application treatments that substantially disturbed the soil, broadcast then disked and subsurface incorporation, had the greatest cumulative leachate depths, consistent with the hypothesis that loosening the soil surface and decreasing bulk density increase infiltration (e.g., Unger 1992). For the early events, leachate depths for the broadcast then disked manure treatment were substantially elevated above the other three treatments. For the final three irrigation events, the two treatments for which the surface was not disrupted (control and broadcast) were virtually equal in leachate depth as were the two manure treatments for which the surface was disrupted by disking (broadcast then disked) or slitting (subsurface incorporation). As reported by Feyereisen and Folmar (2009), leachate depths from the lysimeters in this study were consistent with published saturated hydraulic conductivities for these soils and thus support the hypothesis that treatment differences observed in the lysimeters would be reflected in the field.

Fractionation of P in leachate pointed to a significant role of particulate P transfer as well as the overwhelming contribution of organic P to dissolved P in leachate (figure 4). Particulate P was strongly tied to total P concentration in leachate ( $r^2 > 0.94$ ), accounting for at least 58% to 64% of total P. The largest concentrations of particulate P were associ-

ated with the first rainfall simulation followed by the first irrigation event (figure 4a). Findings clearly implicated particulate P as a primary fraction of leached P, consistent with studies elsewhere that have evaluated leaching of P from manured soils (Toor et al. 2005; Schelde et al. 2006; Kleinman et al. 2009). In those studies, however, liquid manures were evaluated. The transfers of particulate P were indicative of macropore flow but do not distinguish between soil and manure sources. As with total P, initial concentration of particulate P was highest for the subsurface applied litter manure treatment; broadcast and disked manure treatments were intermediate. Whether the particulate P derived directly from litter or represented soil solids that sorbed dissolved P from the litter could not be determined.

Total dissolved P concentrations from the initial rainfall simulation were nearly five times greater in leachate from subsurface incorporation manure treatment than the broadcast manure treatment, which in turn was at least three times greater than the disked and control treatments. Most of the total dissolved P (60% to 72%) was in organic form for both the manured treatments and the unamended control, with dissolved organic P trends roughly tracking total dissolved P. The contribution of dissolved organic P to leachate P confirmed concerns of dissolved organic P mobility in the environment. Hill and Cade-Menun (2009) observed that Delmarva soils that received poultry litter did not retain organic P fractions contributed by litter, positing that the organic P was either transformed or removed by runoff. Various authors have reported significant, even dominant, fractions of organic P in leachate from manure-amended soils (Chardon et al. 1997; Toor et al. 2003; McDowell and Koopmans 2006; Kleinman et al. 2009). While dissolved organic P from treatments recently receiving manure was readily attrib-

**Figure 4**  
 Individual event concentrations for (a) particulate phosphorus (P), (b) dissolved organic P, and (c) dissolved reactive P by manure treatment. The first and last events were rainfall simulations; the other events were irrigations. Each half bar represents one standard error.



uted to the manure source, particularly from a monogastric animal that is unable to digest phytate P in feed (Hill and Cade-Menun 2009), it is unclear why dissolved organic P constituted such a significant fraction of total dissolved P in leachate from the unmanured control (68%). This relative contribution suggests that organic P sources in soils may persist over time, as these soils had last previously received litter three years prior to the current study.

**Comparison of Soil Block Means of Total Phosphorus Loss.** The total P loss from soil block 1 (0.64 kg ha<sup>-1</sup> [0.57 lb ac<sup>-1</sup>]) was elevated above the losses from the other soil blocks (table 4), and the test for differences among soil block total P means indicated that there were differences ( $F_0 = 7.06$  [ $p < 0.0037$ ]). Soils in block 1 differed from other blocks on the basis of sand content throughout the solum and depth to sandy substrate (table 4). Average sand content of soil horizons in block 1 was 51%, and depth to the bottom of the argillic horizon, or sandy substrate, averaged 42 cm (16.5 in). In contrast, average sand content of the remaining blocks was 31% to 44%, and depth to sandy substrate averaged 44 to 54 cm (17 to 21 in). Given the higher hydraulic conductivity of sand, we expected greater leaching depths from the lysimeters in soil block 1. Indeed, the  $F_0$  test for differences among soil blocks indicated differences for cumulative leaching depth ( $F_0 = 2.90$  [ $p < 0.069$ ]) and for total P concentration ( $F_0 = 3.09$  [ $p < 0.058$ ]), and the values for cumulative leaching depth and TP concentration were elevated for soil block 1 (table 4). Although the current experiment was not designed to test the efficacy of the litter application treatments on various soil types, blocking by soil variability within the experimental area revealed that soil texture influenced the rapid incidental transfer of phosphorus after poultry litter application. The results point to the importance of edaphic factors in the impact of litter application on P leaching losses.

## Summary and Conclusions

We simulated precipitation equivalent to that which normally occurs over the period between litter application and corn establishment (28.5 cm [11.2 in]) and observed losses of P ranging from 0.48 kg ha<sup>-1</sup> (0.43 lb ac<sup>-1</sup>) for the subsurface incorporator to 0.19 kg ha<sup>-1</sup> (0.17 lb ac<sup>-1</sup>) for the unamended control. Broadcasting manure, which results

**Table 4**

Comparison of cumulative total phosphorus (TP) loss, cumulative leachate depth, and average TP leachate concentration by soil block. Also shown are average depth to the sandy subsoil and sand content by soil layer for each soil block.

	Depth (cm)	Soil block				
		1	2	3	4	5
Cumulative TP loss (kg ha <sup>-1</sup> )		0.64 (0.20)	0.34 (0.24)	0.17 (0.08)	0.16 (0.03)	0.30 (0.22)
Cumulative leachate depth (cm)		16.2 (2.3)	13.9 (1.2)	12.7 (1.8)	13.5 (1.0)	14.5 (3.1)
TP concentration (mg L <sup>-1</sup> )		0.40 (0.27)	0.22 (0.18)	0.12 (0.04)	0.08 (0.02)	0.08 (0.01)
Average depth to sandy subsoil (cm)		42	48	44	54	50
Sand (%)	0 to 5	43	39	35	30	36
	5 to 15	44	37	35	35	36
	15 to 30	53	42	36	18	23
	30 to 45	71	37	46	35	28
	45 to 60	43	66	69	48	32

Note: Parenthetical values are standard deviations.

in adverse impacts to surface runoff and ammonia volatilization, did not significantly increase cumulative losses relative to the control, although losses were elevated. Incorporation of litter by disking had losses similar to those observed with broadcasting and not significantly different from the control but is incompatible with no-till management. Furthermore, soils with the highest sand content and shallowest depth to the sandy subsoil yielded the greatest P leaching losses (0.64 kg ha<sup>-1</sup> [0.57 lb ac<sup>-1</sup>]). On the Delmarva Peninsula where P loss from high-P soils is primarily via groundwater, this study shows that subsurface poultry litter incorporation can increase total P leaching losses. Results clearly point to the need for caution when employing subsurface litter incorporation to areas where leaching losses of P are of concern.

Our findings also point to the potential to reduce total P losses associated with this slit-type litter incorporator by designing the incorporator to mix the litter with the soil in the trench. The total P losses for the subsurface litter incorporation method were primarily driven by concentration, especially during the first rainfall simulation event. To reduce the leachate concentration, we propose additional mixing of the litter with the soil in the trench to better disperse the pocket of litter and increase P sorption to the soil. This could be achieved with either a leading or trailing disk using modified zone tillage equipment without substantially increasing surface residue disturbance. The objective of the design adjustment would be to mimic the broadcast then disked manure treatment, which exhibited the lowest cumulative total P loss of the litter application methods. Clearly,

opportunities exist to improve litter incorporation techniques on the Delmarva Peninsula.

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### Disclaimer

Mention of trade names does not imply endorsement by USDA ARS.

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