Evaluation of Phosphorus Transport in Surface Runoff from Packed Soil Boxes

Peter J. A. Kleinman,* Andrew N. Sharpley, Tamie L. Veith, Rory O. Maguire, and Peter A. Vadas

ABSTRACT

Evaluation of phosphorus (P) management strategies to protect water quality has largely relied on research using simulated rainfall to generate runoff from either field plots or shallow boxes packed with soil. Runoff from unmanured, grassed field plots (1 m wide × 2 m long, 3–8% slope) and bare soil boxes (0.2 m wide and 1 m long, 3% slope) was compared using rainfall simulation (75 mm h^{-1}) standardized by 30-min runoff duration (rainfall averaged 55 mm for field plots and 41 mm for packed boxes). Packed boxes had lower infiltration (1.2 cm) and greater runoff (2.9 cm) and erosion (542 kg ha^{-1}) than field plots (3.7 cm infiltration; 1.8 cm runoff; 149 kg ha^{-1} erosion), yielding greater total phosphorus (TP) losses in runoff. Despite these differences, regressions of dissolved reactive phosphorus (DRP) in runoff and Mehlich-3 soil P were consistent between field plots and packed boxes reflecting similar buffering by soils and sediments. A second experiment compared manured boxes of 5- and 25-cm depths to determine if variable hydrology based on box depth influenced P transport. Runoff properties did not differ significantly between box depths before or after broadcasting dairy, poultry, or swine manure (100 kg TP ha^{-1}). Water-extractable phosphorus (WEP) from manures dominated runoff P, and translocation of manure P into soil was consistent between box types. This study reveals the practical, but limited, comparability of field plot and soil box data, highlighting soil and sediment buffering in unamended soils and manure WEP in amended soils as dominant controls of DRP transport.

Accelerated eutrophication, the biological enrichment of surface waters stemming from anthropogenic inputs of nutrients, is the most common surface water impairment in the United States (USEPA, 1996). For many watersheds, runoff from agricultural soils is responsible for elevated concentrations of P in surface waters, the chief cause of accelerated eutrophication (USGS, 1999). In response to local (Coale et al., 2002) and national water quality and nutrient management initiatives (USDA and USEPA, 1999), nearly all states have implemented guidelines for land application of manure that take into account the potential for P loss in runoff from manure-amended soils. To date, at least 45 states have adopted P site assessment indices to identify agricultural fields that are "critical source areas" of P to surface water; areas where high concentrations of P are found in soils prone to runoff (Sharpley et al., 2003).

The processes by which agricultural soils, and, more specifically, manure management, influence the transport of P in agricultural runoff are well documented. Over the long term, application of manure P to soils at rates greater than annual crop removal results in the accumulation of P in surface soil (Smith et al., 1998). Elevated concentrations of soil P affect water quality through desorption of soluble P forms to runoff water (Sharpley et al., 1981a) as well as through erosion, which preferentially removes soil particles that are enriched in P relative to bulk soil (Sharpley, 1985b). Over the short term (months), application of manure to soils, particularly via broadcasting, temporarily elevates P available to runoff water, due to high concentrations of water-soluble P in manure (Edwards and Daniel, 1993). In addition, low-density organic matter fractions in manure (flocs) are highly susceptible to erosion when manure is broadcast (McDowell and Sharpley, 2002).

The study of P transport in surface runoff from agricultural soils has relied on a variety of research methods. Watershed monitoring represents the most direct evaluation of soil and management effects on water quality because watershed export of P is ultimately the concern to eutrophication. However, only a limited number of studies, mostly of smaller watersheds, have convincingly linked soil and manure management to watershed P export (Sharpley et al., 1991; Smith et al., 1991). Interactions of hydrology (surface and subsurface flow), climate, geomorphology, soils, and management tend to mask causal links between field management and watershed P export (Calhoun et al., 2002).

Field runoff plots of various sizes (2–622 m^2) have been used effectively, in conjunction with either natural or simulated rainfall, to relate soil and manure management to runoff water quality (McDowell and Sharpley, 2001; Gascho et al., 1998; Zhao et al., 2001). Field runoff plots provide control of many landscape variables that potentially confound watershed research. In addition, large numbers of replicated treatments are possible with field plots, facilitating quantitative evaluation and comparison of alternative treatments. For instance, to develop defensible environmental thresholds for P levels in agricultural soils, researchers from at least 29 states are participating in the National Phosphorus Research Project (NPRP), using rain simulators, 2-m-long runoff plots, and a common experimental protocol to quantify soil-specific relationships between soil P and P in runoff (Sharpley et al., 1999, 2002b).

Runoff boxes, typically packed with soil and subjected to simulated rainfall (subsequently referred to as packed boxes), allow for even greater control of confounding variables than do field runoff plots, as soils can be homogenized to minimize significant variability in physical and chemical characteristics. As with field plots, packed boxes have been used to quantify soil P–runoff P rela-

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Abbreviations: DRP, dissolved reactive phosphorus; EDI, effective depth of interaction; SS, suspended solids; TP, total phosphorus; WEP, water-extractable phosphorus.

tionships (Sharpley, 1995; Pote et al., 1999). However, packed boxes are least representative of field and landscape conditions. The hydrology of sieved, packed soil boxes is undoubtedly different from field soils with intact structure, complex horizonation, and the complete array of fine-earth and coarse fragments. In addition, recent studies of P transport using packed boxes have generally relied on bare soils that are highly susceptible to erosion (Sharpley, 1995), in contrast with field plot studies that have included a variety of soil cover and cultivation treatments (Edwards and Daniel, 1993; Torbert et al., 2002; Zhao et al., 2001).

Recently, a series of findings, primarily from packed box studies, have provided the quantitative basis for developing P availability coefficients in some P site assessment indices (Sharpley et al., 2003). Phosphorus availability coefficients are quantitative indicators of the relative availability of P in mineral fertilizer or manure to be transported in runoff (Leytem et al., 2003). Kleinman et al. (2002a) observed that concentrations of DRP in runoff from packed boxes recently broadcast with various manures or mineral fertilizer at the same rate of TP addition were a function of the WEP concentration of the applied P source. These findings were extended by Kleinman and Sharpley (2003), who examined application rate and timing effects related to WEP in manure, as well as by Brandt and Elliott (2003), who examined runoff P losses from soils that were broadcast with various biosolids. All studies used shallow (5-cm-deep) packed boxes with infiltration properties possibly controlled by box depth rather than soil properties, even though the packed boxes did allow for some drainage via nine, 5-mm-diameter drain holes (Kleinman et al., 2002a).

Use of shallow soil boxes with limited infiltration may affect conclusions regarding manurial P transport. Sharpley (1985a), in experiments using packed soil boxes, reported effective depths of interaction (EDI) between runoff water and soil from 0.1 to 3.7 cm, highlighting the importance of processes affecting P distribution at the soil surface. Elsewhere, Pote et al. (2001) observed that DRP concentration in runoff from field plots broadcast with swine slurry was negatively correlated with infiltration rate. They hypothesized that increasing infiltration resulted in greater translocation of soluble P from the manure below the EDI, into the soil subsurface, where it was unavailable to runoff. Thus, it is possible that poor infiltration resulting from shallow-bottomed soil boxes with restricted water holding capacity could limit translocation of manure P into the soil, resulting in P transport that does not adequately reflect natural soil controls.

Given that results from grassed field plots and bare soil boxes are used interchangeably to calibrate P site assessment indices, the objective of this study was to examine the use of packed boxes in the study of P transport from agricultural soils. Specifically, this study was conducted to (i) compare results from unamended grassed field plots with boxes packed with bare soil, particularly with regard to the relationship between DRP in runoff and soil P, and (ii) determine if conclusions regarding manure management effects on runoff P concentrations derived from packed box experiments are influenced by box depth.

MATERIALS AND METHODS

Two agricultural soils, Hartleton channery-silt loam (loamy-skeletal, mixed, active, mesic Typic Hapludult) and Honeoye loam (fine-loamy, mixed, active, mesic Glossic Hapludalf), were selected for this study. These soils are widespread in the northeastern United States, particularly in New York and Pennsylvania, and have different parent materials. Hartleton soils are derived from shale and sandstone residuum and are acidic, whereas Honeoye soils are developed from calcareous glacial till and are alkaline.

Comparison of Field Plots and Packed Boxes: Experiment 1

Field Plots

Field runoff experiments were conducted on plots established in Hartleton and Honeoye soils representing a broad range of Mehlich-3 P concentrations (44–386 mg kg^{-1} for Hartleton soils, 13–136 mg kg^{-1} for Honeoye soils). Slope gradients varied from 3 to 8%. All soils had established stands of mixed grasses (orchard grass, *Dactylis glomerata* L.; timothy, *Phleum pretense* L.; tall fescue, *Festuca arundinacea* Schreb.; white clover, *Trifolium repens* L.) or alfalfa (*Medicago sativa* L.), cut to a 7-cm height, and had not received manure or mineral fertilizer in the six months before the runoff experiment. A total of 8 plots were established on Hartleton soils and 18 plots on Honeoye soils. At each location, one pair of 2-m-long and 1-m-wide runoff plots was installed, isolated on the upper three sides by steel frames driven 5 cm into the soil and extending 5 cm above the soil. At the lower end of each plot, a gutter was installed, inserted 5 cm into the soil with the upper edge level with the soil surface. The gutter was equipped with a canopy to exclude direct input of rainfall and a 2-cm plastic tube was used to route runoff water from the gutter to plastic collecting vessels.

Rain simulations were conducted on two successive days following the protocol of the National Phosphorus Research Project (2001). Portable rain simulators (Humphry et al., 2002) equipped with TeeJet 1/2 HH SS 50 WSQ nozzles (Spraying Systems Co., Wheaton, IL) were placed approximately 3 m above the soil surface. At this height, simulated rainfall achieves approximately 90% terminal velocity and has a coefficient of uniformity of >0.80 within the 2- × 2-m area directly below the nozzle. On each day, rainfall was delivered at approximately 75 mm h^{-1} until 30 min of runoff was collected. Following each simulation, runoff water was thoroughly stirred to resuspend settled particles and immediately sampled. A filtered (0.45 μm) subsample was obtained within 24 h. Runoff samples were stored at 4°C before laboratory analysis.

While antecedent soil moisture was expected to range widely between plots before the first event, soils were expected to be at field capacity before the second event, as confirmed by capacitance sensor (Theta Probe; Delta-T Devices, Cambridge, UK). Because variability in antecedent soil moisture affects both hydrology and P transport, results from only the second runoff event were used to assess trends in P transport related to soil P.

Packed Runoff Boxes

Rainfall simulations were conducted following the National Phosphorus Research Project packed-box protocol (National

Phosphorus Research Project, 2001). This protocol uses 1-m-long × 20-cm-wide × 5-cm-deep stainless steel boxes, with back walls 2.5 cm higher than the soil surface, and 5-mm diameter drainage holes in the base. Cheesecloth was placed on the bottom of each box before soils were packed. At the lower end of each box, a gutter equipped with a canopy channeled runoff water to collection containers (Kleinman et al., 2002a).

For this experiment, surface horizons (0–20 cm) of Hartleton and Honeoye soils representing a variety of soil test P concentrations were collected, field-sieved to pass through a 1.4-cm-diameter opening, air-dried, and thoroughly mixed. To ensure homogeneity of the individual soils, the effectiveness of mixing was evaluated by conducting Mehlich-3 P extraction on six subsamples from each soil and determining the coefficient of variation (standard deviation divided by mean Mehlich-3 P concentration) for each soil. For both soils, the coefficient of variation was <0.05. Soils were packed into boxes to achieve an approximate bulk density of 1.3 to 1.5 g cm^{-3}.

Packed boxes ($N = 8$ for each soil) were placed under the rain simulator, inclined to a 3% slope gradient, and staggered so that, during rainfall simulation, splash from one box would not be intercepted by another box. Soils were first saturated using the rainfall simulator (75 mm h^{-1} until ponding was observed, approximately 10 min) and allowed to drain for 72 h before the initial rainfall event. All soils were approximately at field capacity at the start of the first runoff-generating event, ensuring that hydrologic variability related to antecedent moisture was minimized. Rain simulations and runoff collection procedures followed those described for the field plots.

Effect of Box Depth and Manure Application on Phosphorus Transport: Experiment 2

Interactions among box depth, broadcast manure, and timing and sequence of runoff event on runoff P losses were assessed using a modified version of the packed box protocol described above. For this experiment, an additional set of boxes was constructed, with all features similar to the National Phosphorus Research Project boxes except that the modified boxes were 25 cm deep.

Surface horizons of low-P Hartleton (average Mehlich-3 P = 16 mg kg^{-1}) and Honeoye soils (average Mehlich-3 P = 21 mg kg^{-1}) were collected, processed in the fashion described above, and analyzed for Mehlich-3 P. Following mixing, the coefficient of variation for Mehlich-3 P of six randomly selected samples was <0.05 for both soils. Soils were packed into the boxes to obtain a bulk density of 1.3 to 1.5 g cm^{-3}. For each soil, eight 5-cm-deep packed boxes and eight 25-cm-deep packed boxes were used.

Three manures were selected to represent a range of animal species, dry matter contents, and P solubilities. Dairy manure, layer poultry manure, and swine slurry were collected, thoroughly mixed, and stored at 4°C for a maximum of one week before analysis. Dairy manure and swine slurry were sampled from the Pennsylvania State University Dairy and Swine Centers at University Park, PA. The dairy manure was from lactating Friesian-style dairy cows (*Bos taurus*) and was scraped from a free stall barn. Swine slurry was from finishing sows (*Sus scrofa domestica*) that was washed into a holding tank and agitated before sampling. Poultry (*Gallus gallus domestica*) manure was from a laying operation in Northumberland County, PA, and was collected directly from the layer house.

Rainfall-runoff simulations were performed before and after manure was broadcast onto the packed boxes following the basic rain simulation and runoff collection protocol described earlier for packed soil boxes (75 mm h^{-1} rainfall, 30-min runoff). Before manure application, two rainfall simulations were conducted on consecutive days to assess trends in runoff P derived from bare soil P only. Three days after the second event, dairy manure, poultry manure, and swine slurry were broadcast onto individual packed boxes at a rate corresponding to 100 kg TP ha^{-1}. A control treatment (zero manure application) was left for comparison. Each treatment was conducted in duplicate. Consecutive rainfall-runoff simulations were conducted three and four days after the manure was applied. Runoff was collected, processed, and analyzed as described above.

To assess possible differences in soil moisture related to box depth, volumetric soil water content was measured by capacitance sensor. Before and after each rainfall simulation event, two measurements were obtained from the top and bottom ends of every packed box (0- to 4-cm depth), with special attention paid to minimizing disturbance during insertion of the capacitance sensor.

After the last rainfall simulation event, soils from each box were sampled to assess soil P accumulation with depth. For the 5-cm-deep boxes, 0- to 1-, 1- to 3-, and 3- to 5-cm depth increments were sampled. For the 25-cm-deep boxes, additional depth increments of 5- to 10- and 10- to 25-cm were sampled.

Chemical Analyses

Soil Analysis

Soils used in packed box experiments were sampled before the rainfall simulations for Mehlich-3 P analysis. In addition, for each field plot, ten 5-cm-deep soil samples were collected with a 2-cm-diameter stainless steel probe following the rainfall simulations and mixed thoroughly to provide a composite soil sample. All soils were air-dried, sieved (2 mm), and analyzed for Mehlich-3 P by shaking 2.5 g of soil with 25 mL of Mehlich-3 solution (0.2 *M* CH_3COOH + 0.25 *M* NH_4NO_3 + 0.015 *M* NH_4F + 0.013 *M* HNO_3 + 0.001 *M* EDTA) for 5 min (Mehlich, 1984). Extract P was determined colorimetrically, by a modified method of Murphy and Riley (1962), with a spectrophotometer wavelength of 712 nm. Soil pH was determined by mixing air-dry soil with distilled water (5 g to 5 mL).

Soil samples collected from packed boxes at the conclusion of Experiment 2 were air-dried, sieved (2 mm), and analyzed for Mehlich-3 P and WEP. Water-extractable soil P was measured by shaking 0.5 g of soil in 5 mL of distilled water for 1 h, filtering the supernatant through a Whatman (Maidstone, UK) no. 1 paper filter, and determining P colorimetrically.

Runoff Water Analysis

Dissolved reactive P was determined on 0.45-μm-filtered runoff water by the colorimetric method described for soil extracts. Total P was measured on unfiltered runoff water by modified semimicro Kjeldahl procedure of Bremner (1996). Runoff water was also analyzed for suspended solids (SS) by evaporating 200 mL of unfiltered runoff water in an oven at 70°C and weighing the remaining material.

Manure Analysis

Manure was analyzed for TP by modified semimicro Kjeldahl procedure (Bremner, 1996). Water-extractable P was analyzed by the method of Kleinman et al. (2002b). One gram dry-weight equivalent fresh manure was shaken with 200 mL of distilled water on an end-over-end shaker for 60 min. The mixture was then centrifuged (about 2900 × *g* for 20 min to facilitate filtration) and filtered through a Whatman no. 1 filter paper. Filtrate P was determined colorimetrically. Manure pH was measured after mixing 1 g (equivalent dry weight) of fresh manure with 100 mL distilled water. Dry matter content of all manures was determined gravimetrically after oven-drying manures at 70°C for 48 h.

Statistical Analyses

Runoff P concentrations (mg L^{-1}) and losses (kg ha^{-1}) were logarithmically transformed to conform with assumptions of normality and equal error variances. As DRP and TP were often less than one (mg L^{-1} or kg ha^{-1}), these variables were transformed for analysis by adding 1 to the P concentration and determining the logarithm of that sum so that no negative values were obtained (Neter et al., 1996). Treatment effects were evaluated by one-way ANOVA for the field plot–packed box comparisons (Experiment 1) and by general linear model for the box–depth comparisons (Experiment 2), along with Tukey's mean separation. Relationships between soil and runoff variables were quantified by least squares regression, and differences in regression parameters were assessed by a homogeneity of variance test (Gomez and Gomez, 1976). Treatment differences discussed in the text were significant at $\alpha \leq 0.05$. Analyses, with the exception of homogeneity of variance of regression coefficients, were performed using Minitab's statistical software (Release 13; Minitab, 2001) and SAS Version 8 (SAS Institute, 1999).

RESULTS AND DISCUSSION

Experiment 1: Comparison of Field Plots and Packed Boxes

Rainfall, Infiltration, and Runoff

Rainfall and hydrologic variables differed significantly between field plots and packed boxes. Because rain simulations were standardized to produce 30 min of runoff, differences in rainfall infiltration (described below) affected the time needed for runoff to occur, resulting in significantly different amounts of rainfall that were applied (Table 1). Field plots were subjected to an average depth of 54 mm rainfall compared with 41 mm applied to packed boxes. Rainfall depth–duration return periods (rainfall depths ranged from 38 to 73 mm, durations ranged from 30 to 38 min) were from 5 to 50 yr (Pennsylvania Department of Environmental Resources, 1983), whereas intensity–duration return periods (intensity = 75 mm h^{-1}) were roughly 10 to 100 yr (Aaron et al., 1986).

Such differences in rainfall return periods result from the nonlinear nature of intensity–duration and depth–duration relationships, as well as the different functions used to calculate return periods. The different rainfall depths also point to one of the inherent risks of comparing fixed-time runoff data; studies relying on fixed-time runoff events routinely result in significant differences in rainfall between treatments (e.g., Pote et al., 1999; Torbert et al., 2002; Daverede et al., 2003). Even so, the range of return periods across packed boxes and field plots is consistent with that found in other studies on P transport where significant differences in rainfall depths were not observed. For instance, Zhao et al. (2001), evaluating tillage and nutrient source effects on runoff water quality from field plots, used a rainfall simulator that produced mean rainfall intensities from 64 to 71 mm h^{-1} corresponding with local intensity–duration return periods of roughly 40 to 90 yr.

Infiltration was significantly greater in the field plots than in the packed boxes (Table 1), but did not differ significantly between soils, which had similar particle size distributions. Differences in infiltration between field plots and packed boxes probably reflect the role of preserved soil structural attributes, such as intact macropores, that were not present in the sieved soils of the packed boxes (Quisenberry and Phillips, 1976). Surface sealing due to aggregate dispersion by direct raindrop impact also probably reduced infiltration into the bare soils of the packed boxes (McIntyre, 1958). Results from Experiment 2, described below, suggest that the drainage design of the packed boxes (nine 5-mm drainage holes) did not significantly impede infiltration into the sieved soils. Indeed, rainfall infiltration into packed soil boxes persisted throughout the runoff event, as runoff depths (25.0–36.5 mm) did not achieve 100% of rainfall (37.5 mm) over the 30-min runoff event (Table 1).

Differences in infiltration clearly affected runoff depth, which was negatively related to infiltration for both field plots (runoff = 3.3 − 0.4 × infiltration; r^2 = 0.68) and packed boxes (runoff = 3.6 − 0.5 × infiltration; r^2 = 0.76). Significantly less runoff was produced from the field plots than from the packed boxes, and no significant differences were observed between soils (Table 1).

Suspended Solids, Total Phosphorus, and Dissolved Reactive Phosphorus Concentrations in Runoff

As expected, runoff from field plots and packed boxes contrasted with regard to SS concentration (g L^{-1}),

Table 1. Mean rainfall, hydrologic, and runoff quality properties from field plots and packed boxes evaluated in Experiment 1.

	Field plots		Packed boxes	
Property†	Hartleton	Honeoye	Hartleton	Honeoye
Rainfall, mm	56b‡	52b	40a	41a
Infiltration, cm	4.0d	3.3cd	1.3c	1.0c
Runoff, cm	1.6e	1.9e	2.7f	3.1f
Runoff SS, g L^{-1}	1.56h	0.21g	2.47i	1.79h
Runoff SS, kg ha^{-1}	253jk	44j	592k	491k
Runoff TP, mg L^{-1}	1.41m	0.37l	3.66n	2.17m
Runoff TP, kg ha^{-1}	0.23o	0.08o	0.86p	0.68p
Runoff DRP, mg L^{-1}	0.35q	0.07q	0.22q	0.08q
Runoff DRP, kg ha^{-1}	0.06s	0.01r	0.05rs	0.03rs

† SS, suspended solids; TP, total phosphorus; DRP, dissolved reactive phosphorus.
‡ Means in each row are grouped by lowercase letter based on Tukey's mean separation.

which was greater from the packed boxes than from the field plots (Table 1). These differences reflect the presence of a protective grass or alfalfa canopy in the field plots, compared with the exposed, bare soil of the packed boxes. In addition, sieving and packing soils into boxes destroys larger soil aggregates, increasing the availability of fine particles to runoff, and possibly decreasing the stability of remaining aggregates. Significant differences in SS concentration were also detected between the two soils, with greater SS concentrations from the Hartleton soil than from the Honeoye soil for both field plots and packed boxes.

Runoff TP concentrations were strongly related to SS concentrations in runoff from Hartleton field plots and weakly related to SS concentrations from Honeoye soil boxes (Table 2), reflecting the importance of particulate P to TP concentrations in runoff. Even though particulate P was not directly measured in this study, particulate P probably accounted for most of the difference between TP and DRP in runoff. For all packed boxes, DRP contributed from 1 to 8% of TP in runoff, whereas for all field plots, DRP contributed 5 to 38% of TP. The larger contribution of DRP to TP in runoff from field plots reflects the lower erosion from the grass-covered field plots than from the bare soils of the packed boxes and possibly dissolved P release from plant residue at the surface of the field plots.

Regressions between runoff DRP and soil P concentrations are used to derive P extraction coefficients (slope of the regression) which, in turn, are input to process-based P transport models and P site assessment indices (Sharpley et al., 2002a). In this study, field plots and packed boxes produced a variety of regressions between DRP concentration in runoff and Mehlich-3 soil P (Table 2). Within individual soils, regression slopes appeared to differ between field plots and packed boxes, but the differences were inconsistent. For instance, regression slopes for Hartleton soil were greater for the field plots than for the packed boxes but the differences were not statistically significant. Regressions for Honeoye were not as strong ($r^2 = 0.53$–0.83) as those for Hartleton ($r^2 = 0.87$–0.93), particularly for the field plots. Unlike the Hartleton soil, regression slopes for the Honeoye soil were lower for field plots than for packed boxes. However, when all data were evaluated in aggregate, the relationship between DRP concentration and Mehlich-3 P (Fig. 1a) was effectively described by a single equation, $\log(\text{DRP} + 1) = 0.009 + 0.0005 \times$ Mehlich-3 P ($r^2 = 0.88$).

Extraction coefficients relating DRP in runoff to Mehlich-3 P were in the range of those reported in the literature, provided that data from the literature were transformed [log(DRP + 1)] to correspond with those in this study. Extraction coefficients for grassed field plots on acidic soils ranged from 0.0005 to 0.0011 (Pote et al., 1999; McDowell and Sharpley, 2001), while those for alkaline soils varied from 0.0002 to 0.0009 (Torbert et al., 2002). For packed boxes, Sharpley (1995) reported extraction coefficients ranging from 0.0008 to 0.0014 for acidic soils and 0.0006 to 0.0009 for alkaline soils, while Fang et al. (2002) reported an extraction coefficient of 0.0018 for alkaline soils. Analysis of regressions generated by these studies supports the findings of Experiment 1. No significant differences in regression slopes (DRP in runoff vs. Mehlich-3 P) were observed between field plots and packed soil boxes or between alkaline and acidic soils. When data from all of these studies were analyzed collectively, the ensuing regression equation was similar to that obtained from Experiment 1, although the relationship was not as strong [$\log(\text{DRP} + 1) = 0.066 + 0.0005 \times$ Mehlich-3 P; $r^2 = 0.54$].

Comparison of runoff DRP–soil P trends between soils, as well as between field plots and packed boxes, can be biased by unequal ranges of Mehlich-3 P concentrations. In Experiment 1, the ranges of Mehlich-3 P concentrations of the Honeoye soil were considerably narrower (13–136 mg kg^{-1} for the field plots; 21–80 mg kg^{-1} for the packed boxes) than those of the Hartleton soil (44–386 mg kg^{-1} for the field plots; 16–410 mg kg^{-1} for the packed boxes). McDowell and Sharpley (2001) identified nonlinear relationships between DRP concentrations in runoff and Mehlich-3 P, with a Mehlich-3 P threshold of approximately 200 mg kg^{-1} separating linear regressions of different slopes. Their results suggest that a range of Mehlich-3 P concentrations falling on one side or the other of the threshold would skew linear regression, such that soils with Mehlich-3 P below the threshold would produce a significantly lower regression slope than soils above the threshold. However, in this study, no consistent differences in regression slopes were observed on that basis and regression slopes for Honeoye soils were not significantly different from those obtained from Hartleton soils (Table 2). Indeed,

Table 2. Regression equations relating total phosphorus (TP) with suspended solids (SS) in runoff and dissolved reactive phosphorus (DRP) in runoff with Mehlich-3 soil phosphorus (M3P) for field plots and packed boxes evaluated in Experiment 1.

Soil	Method	Regression equation	r^2	N
		TP (mg L^{-1}) vs. SS (g L^{-1})		
Hartleton	field plots	$\log(\text{TP} + 1) = 0.1 + 0.3\text{SS}$	0.82	8
	packed boxes	$\log(\text{TP} + 1) = 0.5 + 0.1\text{SS}$	0.20	8
Honeoye	field plots	$\log(\text{TP} + 1) = 0.1 + 0.1\text{SS}$	0.02	18
	packed boxes	$\log(\text{TP} + 1) = 0.4 + 0.1\text{SS}$	0.53	8
		DRP (mg L^{-1}) vs. M3P (mg kg^{-1})		
Hartleton	field plots	$\log(\text{DRP} + 1) = -0.005 + 0.0007\text{M3P}$	0.93	8
	packed boxes	$\log(\text{DRP} + 1) = 0.017 + 0.0004\text{M3P}$	0.87	8
Honeoye	field plots	$\log(\text{DRP} + 1) = 0.015 + 0.0003\text{M3P}$	0.53	18
	packed boxes	$\log(\text{DRP} + 1) = -0.002 + 0.0008\text{M3P}$	0.83	8

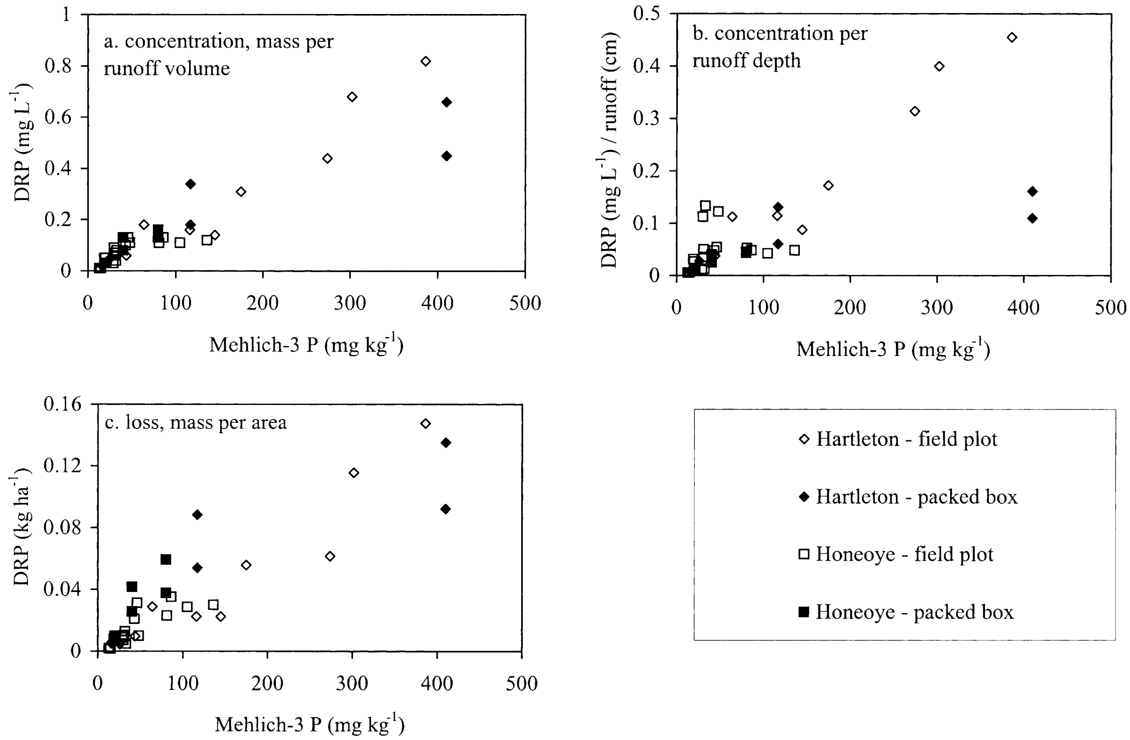

Fig. 1. Relationship of Mehlich-3 soil P to dissolved reactive phosphorus (DRP) in runoff from field plots and packed boxes by (a) concentration, (b) loss, and (c) concentration per runoff depth.

other runoff studies that have included broad ranges of Mehlich-3 P concentrations in a variety of soils (Sharpley, 1995; Torbert et al., 2002) have similarly reported linear relationships between runoff DRP and Mehlich-3 P, indicating that nonlinear trends are not universal.

Normalizing Runoff Properties to Address Variability in Runoff, Contributing Area, and Rainfall

Because variability in runoff, rainfall, and contributing areas is common to many studies of DRP transport, we compared the effects of different normalization approaches on relationships between DRP (mg) and Mehlich-3 soil P in runoff for all data obtained from Experiment 1. Specifically, DRP mass in runoff was divided by catchment area, runoff, rainfall, area × runoff, area × rainfall, runoff × rainfall, and area × runoff × rainfall. As summarized in Table 3, normalizing procedures resulted in widely differing regression equations and r^2 values. Normalizing by catchment area provided the best r^2 values for regressions, illustrating the importance of this variable to DRP loading in runoff. Normalizing on the basis of rainfall depth consistently resulted in the lowest r^2 values. As rain simulation events were controlled for runoff duration (30 min), and runoff from plots and boxes tended to reach equilibrium flow and DRP concentration within 15 min of runoff initiation (Sharpley et al., 1981a; Sharpley and Kleinman, 2003), variability in rainfall depth was not expected to play a dominant role in P release from unamended soil.

Pote et al. (1999) found that they could improve regressions relating DRP concentration in runoff (mg L^{-1}) to Mehlich-3 soil P by dividing DRP by runoff depth. Although concentration data already reflect runoff depth (concentration is the mass of P per runoff volume, and includes runoff depth in the determination of runoff volume), they observed a general positive correlation between DRP concentration and runoff depth, the antithesis of a dilution effect. They attributed the correlation of DRP concentration and runoff depth to translocation of soluble P out of the EDI in soils with high infiltration and low runoff. When they divided the concentration of DRP in runoff by runoff depth, Pote et al. (1999) observed an improved relationship with Mehlich-3 P

Table 3. Regression equations relating Mehlich-3 soil phosphorus (M3P, mg kg^{-1}) with dissolved reactive phosphorus (DRP) in runoff (mg) normalized by catchment area, runoff depth, and rainfall depth (Experiment 1).

DRP in runoff (mg) divided by	Regression equation	r^2
Area (cm^2)	normalized DRP = −0.00004 + 0.000005M3P	0.83
Runoff (cm)	normalized DRP = 0.0152 + 0.0007M3P	0.58
Rainfall (cm)	normalized DRP = 0.0113 + 0.0007M3P	0.52
Area (cm^2) × runoff (cm)	normalized DRP = 0.000008 + 0.000002M3P	0.87
Area (cm^2) × rainfall (mm)	normalized DRP = −0.0000006 + 0.0000001M3P	0.72
Runoff (cm) × rainfall (mm)	normalized DRP = 0.0067 + 0.0004M3P	0.42
Area (cm^2) × runoff (cm) × rainfall (mm)	normalized DRP = 0.0000003 + 0.00000003M3P	0.87

Table 4. Initial properties of Hartleton and Honeoye soils used in Experiment 2.

Soil	Particle size distribution: Sand	Silt	Clay	Mehlich-3 P	Water-extractable P	P sorption saturation	pH (1:1 water)
	%			mg kg^{-1}		%	
Hartleton	41	32	27	16	2.6	1.9	5.4
Honeoye	45	29	26	21	2.8	2.9	7.7

across the different soils. However, when concentration data from Experiment 1 were normalized by runoff depth, regressions of DRP in runoff and Mehlich-3 soil P became more variable (Fig. 1b). No significant differences in regression slopes (Table 3) were observed between field plots and packed boxes or between soils, but significant differences were observed between field plots and packed boxes of the Hartleton soil. One key difference that may explain the discrepancy with the findings of Pote et al. (1999) is the lack of a significant correlation between runoff depth and DRP concentration in Experiment 1 data. Torbert et al. (2002) also found that normalizing by runoff depth did not improve regressions of runoff DRP and Mehlich-3 soil P. These results suggest that translocation of soluble P out of the EDI of unmanured soils is not a dominant factor controlling runoff DRP concentrations from field plots or packed boxes.

Another common means of presenting runoff data is as mass exported per standardized contributing area, referred to as "loss" (kg ha^{-1}). When runoff results from Experiment 1 were calculated in this way, conclusions regarding field plot and packed box trends were consistent with those derived from concentration data (g kg^{-1} or mg kg^{-1}). Specifically, for a given soil, SS and TP losses were greater from packed boxes than from field plots and DRP losses were similar between field plots and packed boxes (Table 1). In addition, DRP losses in runoff were strongly related to Mehlich-3 soil P (Fig. 1c). As with DRP concentration, a single regression equation predicted DRP losses when all data were combined [$\log(\text{DRP loss} + 1) = 0.002 + 0.0001 \times \text{Mehlich-3 P}$; $r^2 = 0.82$). Thus, differences in runoff depths and catchment areas of field plots and packed boxes, as they affected losses of SS, TP, and DRP, did not significantly alter conclusions drawn from concentration data.

Experiment 2: Effect of Box Depth and Manure Application on Phosphorus Transport

Influence of Box Depth on Phosphorus Transport from Bare Soils

Properties of both soils used in the packed box depth experiments were similar, with the exception of pH, which was expected due to differing mineralogies (Table 4). Rainfall depths varied between soils and box depths (Table 5), with the most rainfall applied to the Honeoye soils on the first runoff event and generally more rainfall applied to the 25-cm boxes than to the 5-cm boxes. Hydrology of the bare soils did not differ consistently between box depths. Infiltration, a key concern given the possibility that the 5-cm-deep boxes create an artificially perched water table, was not significantly different across events or between box depths for the Hartleton soil. While 25-cm-deep boxes allowed greater infiltration than 5-cm-deep boxes for the Honeoye soil, differences were significant only for the first event. Differences in runoff depths were also inconsistent between soils (Table 5), although more runoff was generally produced during the second event than the first event due to greater soil moisture at the start of the second event (data not shown). Indeed, soil moisture was one variable that behaved consistently across box depth treatments; no significant differences in moisture of the upper 4 cm of soil were observed between 5- and 25-cm boxes, either before or after any of the rainfall events (data not shown).

Before manure application, box depth did not appear to affect DRP concentrations in runoff from bare soils (Table 5). For both soils, no significant differences in DRP concentrations were observed between 5- and 25-cm-deep boxes of similar soil–event treatment combinations. Nor were significant differences in TP concen-

Table 5. Mean rainfall, hydrology and runoff water properties for two rainfall-runoff events before broadcasting of manures onto 5- and 25-cm-deep runoff boxes (Experiment 2).

Event sequence	Box depth	*N*	Rainfall	Infiltration	Runoff	SS† in runoff	TP‡ in runoff	DRP§ in runoff
Day	cm		mm	cm		g L^{-1}	mg L^{-1}	
						Hartleton silt loam		
1	5	8	4.2a¶	1.4cd	2.8fg	5.42k	3.69n	0.02p
1	25	8	4.1a	0.9c	3.2gh	5.56k	3.80n	0.02op
2	5	8	4.0a	0.6c	3.4h	4.63k	3.40n	0.01o
2	25	8	4.1a	0.6c	3.5h	3.36j	2.47m	0.01o
						Honeoye loam		
1	5	8	5.1ab	1.7d	3.4gh	1.53i	2.22m	0.03q
1	25	8	6.0b	3.6e	2.4f	0.94i	1.56lm	0.02pq
2	5	8	4.1a	0.7c	3.4h	1.51i	1.98m	0.03pq
2	25	8	4.4a	1.4cd	3.0g	0.73i	1.28l	0.02pq

† Suspended solids.
‡ Total phosphorus.
§ Dissolved reactive phosphorus.
¶ Mean categories (Tukey's) of a single column are represented by lowercase letters.

Table 6. Properties of manures used in comparison of effects of box depth on runoff (Experiment 2).

P source	Dry matter	Total N	Total P	Water-extractable P	pH
	g kg^{-1}	g kg^{-1} (dry weight basis)			
Dairy manure	153	31	5	3	8.0
Poultry manure	334	53	22	4	8.9
Swine slurry	31	107	24	17	7.3

tration observed between box depths for the first runoff event. However, for the second event, TP concentrations were significantly higher from the 5- than from the 25-cm-deep boxes. This difference can largely be explained by differences in erosion, hence particulate P losses. For the second event, mean SS concentrations were greater from the 5-cm boxes than from the 25-cm boxes, although the difference was not statistically significant for the Honeoye boxes (Table 5).

Influence of Box Depth on Phosphorus Transport from Soils Broadcast with Manure

Properties of the three manures ranged widely (Table 6). Total nitrogen (TN) to TP ratios were 6.2:1, 2.4:1, and 4.5:1 for the dairy manure, poultry manure, and swine slurry, respectively. Thus, an N-based manure application rate for silage corn of 300 kg TN ha^{-1} (Beegle, 1999) would result in TP application rates of 48, 125, and 67 kg ha^{-1} for the dairy manure, poultry manure, and swine slurry, respectively. Water-extractable P (dry weight equivalent) was most concentrated in the swine slurry, with concentrations in dairy and poultry manures similar. As a percentage of TP concentration, WEP was roughly 60% of dairy manure TP, 18% of poultry manure TP, and 71% of swine slurry TP.

Surface application of manures resulted in similar increases in runoff DRP and TP concentrations for both 5- and 25-cm-deep boxes (Table 7). Whereas TP and SS concentrations were strongly related in runoff from bare soils before manure application, the regression between these variables was poor after manure was broadcast onto the soil surface [$\log(TP + 1) = 0.04 \times SS + 1.06$; $r^2 = 0.01$], indicating diminishing control of eroded materials (particulate P) on TP in runoff. As a result, the proportion of TP that was DRP increased from <6% before manure application to 22 to 92% after manure

Table 7. Mean runoff water properties after broadcasting dairy, poultry, and swine manures onto 5- and 25-cm-deep runoff boxes packed with Hartleton and Honeoye soils (Experiment 2).

Manure type	Rain event†	Box depth	Rainfall	Infiltration	Runoff	SS‡ in runoff	TP§ in runoff	DRP¶ in runoff
		cm	mm	cm		g L^{-1}	mg L^{-1}	
					Hartleton silt loam			
No manure	3	5	4.1abc#	0.9def	3.2gh	4.07ij	2.90kl	0.60o
Dairy	3	5	4.0ab	1.1def	2.9g	2.73ij	40.28mn	9.28qr
Poultry	3	5	4.0ab	0.8def	3.2gh	3.57ij	41.28mn	14.75r
Swine	3	5	4.0ab	0.3de	3.7gh	3.02ij	96.84n	34.53s
No manure	3	25	4.2abc	0.8def	3.4gh	2.09i	2.22kl	1.38op
Dairy	3	25	4.2abc	0.9def	3.3gh	2.29i	29.20m	9.77qr
Poultry	3	25	4.2abc	0.7def	3.6gh	2.79ij	35.33mn	13.35qr
Swine	3	25	4.1abc	0.1d	4.0h	2.33i	79.11mn	38.24o
No manure	4	5	3.9ab	0.4def	3.6gh	4.14ij	2.51kl	0.12o
Dairy	4	5	4.1abc	0.9def	3.2gh	1.09i	13.66lm	5.51pq
Poultry	4	5	3.9abc	0.4def	3.6gh	4.81ij	6.56lm	4.77pq
Swine	4	5	3.9a	0.3def	3.6gh	5.05j	13.65lm	5.23pq
No manure	4	25	4.1abc	0.4def	3.7gh	2.14i	1.13k	0.19o
Dairy	4	25	4.1abc	0.8def	3.4gh	0.57i	6.64l	4.21pq
Poultry	4	25	4.0abc	0.3de	3.7gh	4.08ij	14.19lm	5.23pq
Swine	4	25	4.1abc	0.2d	3.9gh	3.22ij	17.57lm	7.79q
					Honeoye loam			
No manure	3	5	4.2abc	1.0def	3.3gh	1.84i	2.57kl	0.65o
Dairy	3	5	3.9a	0.5def	3.4gh	2.11i	36.75mn	11.97qr
Poultry	3	5	4.3abc	0.5def	3.8gh	1.85i	39.75mn	14.88r
Swine	3	5	3.9ab	0.2de	3.7gh	2.75ij	92.25n	31.47s
No manure	3	25	4.4c	1.4ef	3.1gh	0.74i	1.02k	0.38o
Dairy	3	25	4.4bc	0.9def	3.5gh	1.66i	30.20m	10.24qr
Poultry	3	25	4.4bc	1.5f	2.9g	0.80i	29.03m	14.20r
Swine	3	25	4.2abc	0.8def	3.4gh	1.10i	53.36mn	27.90rs
No manure	4	5	4.1abc	0.6def	3.5gh	3.39ij	3.27kl	0.04o
Dairy	4	5	3.9ab	0.3def	3.6gh	1.39i	15.81lm	6.06q
Poultry	4	5	4.2abc	0.2d	4.0h	2.29i	15.2lm	5.92q
Swine	4	5	3.9ab	0.3def	3.6gh	1.41i	21.36lm	12.18qr
No manure	4	25	4.3abc	1.1def	3.2gh	0.49i	0.62k	0.09o
Dairy	4	25	4.4c	1.4ef	3.1gh	0.16i	3.99kl	2.87p
Poultry	4	25	4.3abc	1.1def	3.3gh	0.37i	10.25lm	5.65q
Swine	4	25	4.4bc	1.2def	3.2gh	0.58i	10.84lm	8.72qr

† Event number refers to sequence of events in Experiment 2, with Events 1 and 2 occuring on unmanured soils.
‡ Suspended solids.
§ Total phosphorus.
¶ Dissolved reactive phosphorus.
# Mean categories (Tukey's) of each column are represented by lowercase letters.

application. Much of the increase in runoff TP concentrations can be attributed to soluble P additions in the manures. Even so, particulate P, now derived primarily from manure rather than soil, remained a significant contributor to TP, as evidenced by the relatively high SS concentrations from manured soils (Table 7).

Manure application overwhelmed the effect of soil P on runoff P properties, so that individual rain event–manure application treatments generally did not differ significantly between the Hartleton and Honeoye soils (Table 7). Concentrations of DRP in runoff were strongly associated with WEP concentration in applied manure. The effect of manure WEP (g kg^{-1}) on runoff DRP (mg L^{-1}) declined with successive rainfall events, as indicated by the diminishing slopes and r^2 of regression equations from Event 3, the first event following manure application [$\log(\mathrm{DRP} + 1) = 0.06 \times \mathrm{WEP} + 0.65$; $r^2 = 0.63$], to Event 4, the second event after manure application [$\log(\mathrm{DRP} + 1) = 0.04 \times \mathrm{WEP} + 0.41$; $r^2 = 0.47$]. Because of the intense rainfall (75 mm h^{-1}) and long duration of simulated rain storms in this study, declines in runoff DRP concentrations with successive events were large when compared with field studies monitoring runoff from natural rainfall (e.g., Moore et al., 2000).

As with bare soils before manure application, box depth did not significantly affect DRP or TP concentrations in runoff after manure application (Table 7). As DRP concentrations were largely a function of WEP in applied manures, one possibility was that differential translocation of soluble P from the manure into the soil would result in different concentrations of P in the layer of manure and soil interacting with runoff water (the EDI). This was particularly of concern for the manures with high water content, such as the swine slurry, which contained only 3% solids, as immediate infiltration of water from manure could account for substantial translocation of soluble manure P out of the EDI. According to this hypothesis, shallow boxes would prevent soluble P from fully infiltrating into the soil, resulting in artificially elevated concentrations of soluble P at the soil surface that would be prone to runoff. The effect would be exaggerated by differences in rainfall depths between treatments (Table 7), with lower DRP concentrations expected from treatments subjected to greater rainfall. Sharpley (1985a) concluded that soil slope, rainfall intensity, and erosion were the dominant controls of EDI in unamended soils. In this study, slope (3%) and rainfall intensity (75 mm h^{-1}) were held constant and erosion did not differ significantly between box depths. In addition, there were few significant differences in infiltration and runoff between treatments in the final two events, and observed differences were inconsistent (Table 7).

Examination of P distribution in soils after the fourth rainfall event showed few differences between 5- and 25-cm-deep boxes, suggesting that the fate of applied P was not affected by box depth. High concentrations of P were clearly translocated from the broadcast manures into the upper 1 cm of soil, as evidenced by the elevated WEP and Mehlich-3 P of manured soils compared with unmanured soils and subsoils (Table 8). Statistically significant increases in these properties were observed in the 0- to 1-cm soil samples of the dairy manure and swine slurry treatments only. Although WEP and Mehlich-3 P were also somewhat elevated in the 0- to 1-cm soil samples of the poultry manure treatment, they were not significantly different from the subsoil. No significant differences in WEP and Mehlich-3 P were evident at lower depths indicating that translocation of manure P was primarily restricted to the upper 1 cm of soil (Table 8).

Discrepancies in WEP and Mehlich-3 P of the 0- to 1-cm samples point to inherent differences in manure properties controlling soluble P translocation into the soil surface. Specifically, liquid in the dairy manure and swine slurry probably infiltrated at time of broadcasting, translocating high concentrations of soluble P into the surface of the soil. Elsewhere, Hill and Baier (2000) observed that approximately 80% of TP in a swine slurry was associated with freely draining manure water. It is unlikely that any P was translocated into the soil at time of poultry manure broadcasting due to its relatively low moisture content, and very little P appears to have been

Table 8. Mean water-extractable P and Mehlich-3 P of manured soils packed into 5- and 25-cm-deep boxes following two 30-min runoff events (Experiment 2).

	Broadcast with dairy manure				Broadcast with poultry manure				Broadcast with swine slurry			
	5-cm box		25-cm box		5-cm box		25-cm box		5-cm box		25-cm box	
Soil depth	Hartleton	Honeoye	Hartleton	Honeoye	Hartleton	Honeoye	Hartleton	Honeoye	Hartleton	Honeoye	Hartleton	Honeoye
cm	mg kg^{-1}											
							Water-extractable P					
0–1	33.5a†	34.8a	46.4a	13.9ab	5.0b	3.4b	11.9b	7.8b	13.7ab	28.3a	25.5ab	43.2a
1–3	2.5b	3.2b	5.5b	10.3b	2.1b	2.9b	6.0b	3.3b	3.7b	4.3b	2.7b	3.9b
3–5	2.2b	2.9b	3.2b	2.2b	3.5b	2.7b	2.4b	2.7b	6.3b	2.7b	2.2b	3.1b
5–10	NA‡	NA	2.7b	2.6b	NA	NA	2.7b	3.1b	NA	NA	2.1b	2.9b
10–25	NA	NA	3.0b	2.5b	NA	NA	4.8b	2.9b	NA	NA	2.1b	3.3b
							Mehlich-3 P					
0–1	130.0c	135.7c	156.4c	83.07cd	47.7d	24.5d	32.0d	76.3cd	55.8cd	112.9c	173.5c	194.8c
1–3	18.3d	24.2d	25.0d	41.6d	16.6d	142.1cd	20.1d	26.3d	25.9d	28.8d	22.6d	23.7d
3–5	20.3d	21.3d	21.9d	20.2d	30.6d	22.1d	15.8d	25.1d	41.5d	20.3d	17.3d	23.4d
5–10	NA	NA	14.5d	18.1d	NA	NA	16.1d	18.7d	NA	NA	18.0d	21.1d
10–25	NA	NA	20.5d	18.7d	NA	NA	38.0d	22.3d	NA	NA	18.0d	21.6d

† Means were separated by Tukey's pairwise comparison, with similar mean categories represented by lowercase letters.
‡ Data not available for the 5-cm-deep box.

translocated by infiltrating rain water. In the field, in soils with improved infiltration, these differences in P translocation may affect P availability to runoff within the EDI. However, in the packed soil boxes, infiltration properties were such that differences in P translocation were not significant below a 1-cm depth. Thus, box depth did not affect P transport in runoff from manured soils.

CONCLUSIONS

Interpretation and extrapolation of results from packed boxes to field plots requires careful consideration of the P transport processes they represent. Comparison of grassed field plots and packed boxes containing bare soils, two common research tools used in validating and calibrating P site assessment indices, confirmed large differences with regard to erosion, hydrology, and rainfall. The exposed, bare soils of the packed boxes were particularly vulnerable to erosion, resulting in significantly greater TP concentrations in runoff. Greater infiltration in the field plots resulted in significant differences in runoff depth, which probably contributed to erosion differences. Significant differences in rainfall depth were observed due to standardization of event lengths on the basis of runoff (30 min). However, consistent relationships between DRP in runoff and Mehlich-3 soil P resulted in a strong, aggregate relationship across field plots and runoff boxes. Indeed, evaluation of runoff DRP and Mehlich-3 P data from the literature revealed no systematic differences in extraction coefficients between field plots and packed boxes. Thus, despite some profound differences in rainfall, hydrology, and erosion, this study suggests that both field plots and packed boxes can be used to produce comparable P extraction coefficients for process-based models and P site assessment indices.

This study also examined whether limited infiltration in shallow soil boxes, as compared with deeper boxes, substantially affects conclusions related to P transport from manured soils. A key concern was that perched water tables in shallow boxes would impede translocation of soluble P from broadcast manures, inflating soluble P release to runoff water and biasing conclusions regarding the control of manure WEP on runoff P. However, depth of packed soil boxes did not affect P concentrations in runoff. The application of high concentrations of WEP in manure to the surface of packed boxes resulted in similar increases in runoff P from 5- and 25-cm-deep boxes. Although significant concentrations of P were translocated from the dairy manure and swine slurry into the surface soil, trends were similar between boxes of different depths. Furthermore, no significant differences were observed below a 1-cm depth, indicating that, at least in packed soil boxes, translocation of manure P below the EDI is not significant.

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