Assessing manure management strategies through small-plot research and whole-farm modeling

A.M. García, T.L. Veith, P.J.A. Kleinman, C.A. Rotz, and L.S. Saporito

Abstract: Plot-scale experimentation can provide valuable insight into the effects of manure management practices on phosphorus (P) runoff, but whole-farm evaluation is needed for complete assessment of potential trade offs. Artificially-applied rainfall experimentation on small field plots and event-based and long-term simulation modeling were used to compare P loss in runoff related to two dairy manure application methods (surface application with and without incorporation by tillage) on contrasting Pennsylvania soils previously under no-till management. Results of single-event rainfall experiments indicated that average dissolved reactive P losses in runoff from manured plots decreased by up to 90% with manure incorporation while total P losses did not change significantly. Longer-term whole farm simulation modeling indicated that average dissolved reactive P losses would decrease by 8% with manure incorporation while total P losses would increase by 77% due to greater erosion from fields previously under no-till. Differences in the two methods of inference point to the need for caution in extrapolating research findings. Single-event rainfall experiments conducted shortly after manure application simulate incidental transfers of dissolved P in manure to runoff, resulting in greater losses of dissolved reactive P. However, the transfer of dissolved P in applied manure diminishes with time. Over the annual time frame simulated by whole farm modeling, erosion processes become more important to runoff P losses. Results of this study highlight the need to consider the potential for increased erosion and total P losses caused by soil disturbance during incorporation. This study emphasizes the ability of modeling to estimate management practice effectiveness at the larger scales when experimental data is not available.

Key words: farm-scale modeling—phosphorus—scale effects—water quality

Efforts to limit eutrophication of fresh water bodies in the United States have prompted research toward developing new agricultural strategies that minimize phosphorus (P) losses from agricultural fields (Carpenter et al. 1998; US Geological Survey 1999; Sharpley 2000). In particular, assessment of the effectiveness of management practices in reducing P losses has become a nationwide effort through the Conservation Effects Assessment Program (USDA Natural Resources Conservation Service 2006). Such research is particularly relevant to livestock farming operations where manure P application in excess of crop requirements leads to soil P accumulation in the soil and an increased risk of P loss to off-farm water bodies through runoff, erosion, and leaching (Wang et al. 1999). Unincorporated surface application of manure to soils has been shown to be a significant source of P loss when runoff occurs soon after manure application (Kleinman and Sharpley 2003).

Surface application of manure remains common in northeastern United States (Kephart 2000; Dou et al. 2001) and can result in high dissolved reactive P (DRP) losses (Romkens et al. 1973; Mueller et al. 1984). Dissolved reactive P is readily available to algae and therefore is a primary control of eutrophication (Sharpley et al. 2003). As a result, manure incorporation by tillage is often recommended to reduce DRP losses from manure amended fields (Sharpley 2003). However, since incorporation can increase sediment-bound P losses through an increased erosion risk, an integrated management strategy must address both DRP and total P losses to be truly effective in controlling whole-farm P losses.

Agricultural management practices are often developed and tested using small plots subjected to artificially-applied rainfall to ensure adequate control over independent variables (e.g., Eghball and Gilley 1999; Daverede et al. 2003). Small plots offer control of many landscape variables—such as climate, land cover, management practice, and soil—that potentially confound research at the broader hillslope and watershed scales. Small-plot experimentation enables a number of replicated treatments and quantitative evaluation of differences between treatments. At the same time, however, the limited area represented by these plots and finite temporal range of rainfall experiments may restrict the ability to accurately extrapolate findings to other inference scales such as long-term, whole-farm systems. Due to the difficulty of conducting assessments over larger spatial and longer temporal scales, research of best management practice effectiveness at the watershed scale has relied heavily on the findings and summaries of plot-scale research, such as those by Yagow et al. (2002) and Gitau et al. (2005).

Agricultural management decisions typically occur at the farm-level. Thus, the economic and environmental effects of agricultural practices should ultimately be evaluated for the whole farm to ensure their utility. Models can aid the spatial and temporal generalization of plot-level research (van Es et al. 1998). Experiments that employ a specific design storm (fixed rainfall intensity and duration) can be generalized through models to incorporate climatic variability. Similarly, models can generalize over a variety of soils and land uses.

In this study, manure management practice effectiveness on surface P loss reduction was evaluated using both controlled plot-

Ana María García is a hydrologist at the North Carolina Water Science Center, US Geological Survey, Raleigh, North Carolina. **Tamie L. Veith** is an agricultural engineer, **Peter J.A. Kleinman** is a soil scientist, **C. Alan Rotz** is an agricultural engineer, and **Lou S. Saporito** is a research support scientist at the Pasture Systems and Watershed Management Research Unit, USDA Agricultural Research Service, University Park, Pennsylvania.

scale research and farm-level modeling. A plot-scale rainfall experiment was conducted during spring 2002 to identify relevant processes of P transport after manure application. The Integrated Farming System Model (IFSM) was applied to an equivalent event-based modeling experiment as well as to the whole farm for a continuous, long-term assessment. Results from plot-scale experimentation and event-based IFSM simulations were compared and farm-level simulations were evaluated to address effects of surface broadcast and immediately incorporated dairy manure on P loss.

Three objectives were addressed: (1) Identify effectiveness of immediate incorporation on reducing P losses from manure-covered crop fields at the plot scale. (2) Compare experimentation and modeling of surface manure incorporation methods for an extreme event at the plot-scale. (3) Assess farm-scale reduction potential of immediate incorporation on DRP and total P losses.

Materials and Methods

Field Site. Experiments were conducted on a 1.3 ha (3.3 ac) field under no-till corn (*Zea mays*) production to assess the alternative manure application strategies of surface application of dairy manure with and without incorporation of the manure by tillage. The field was part of a dairy farm located in the Eastern Allegheny Plateau and Mountains region of Pennsylvania (Natural Resources Conservation Service Major Land Resource Area 127) and was in the last of four years of corn production as part of a rotation that was followed by four years of alfalfa-orchard grass hay. All crops were no-till planted. The field contained two contrasting soils a well drained, Clymer sandy loam (coarse-loamy, siliceous, active, mesic Typic Hapludult); and a somewhat poorly drained, Wharton silty clay loam (fine-loamy, mixed, active, mesic Aquic Hapludult).

Rainfall Experiments. Sixteen 1 × 2 m (3.3 × 6.6 ft) runoff plots were established in the Clymer and Wharton soils. Plots were isolated by steel frames driven 5 cm (2 in) into the soil and extending 5 cm above the soil. At the lower end of each plot, a gutter was inserted approximately 5 cm into the soil with the upper edge level with the soil surface and a canopy fixed above to exclude direct input of rainfall.

Artificially applied rainfall experiments followed a modified version of the National Phosphorus Research Project protocol (Sharpley et al. 2001). Portable rainfall simulators (Humphry et al. 2002) were equipped with TeeJet 1/2 HH SS 50 WSQ (Spraying Systems Co., Wheaton, Illinois) nozzles placed approximately 3 m (10 ft) above the soil surface, delivering simulated rainfall at an intensity of 7.0 to 7.5 cm h^{-1} (2.8 to 3.0 in hr^{-1}) with a coefficient of uniformity within the plots greater than 0.85.

Rainfall experiments were conducted before and after manure application. Plot soils were saturated with the rainfall simulator and then allowed to drain freely so that antecedent moisture was approximately at field capacity at the start of the rainfall-runoff experiments. On June 18 to 21, 2002, rainfall was artificially applied to the plots to generate 30 minutes of runoff, and plot runoff volumes were recorded every 5 minutes. Runoff samples taken throughout the 30-minute period were combined into a single composite sample, and a portion of the sample was promptly filtered (0.45 μm [0.17×10^{-6} in]). Filtered and unfiltered samples were stored at 4°C (39°F) prior to laboratory analysis.

Manure was applied to the runoff plots on June 24 to 26, 2002. To establish treatment conditions, 0.5 kg (1.1 lb) of dairy slurry (10% dry matter) was hand-broadcast onto each plot, equivalent to a rate of 30 kg total P ha^{-1} (34 lb P ac^{-1}). On half of the plots, a hand-operated rototiller was used to incorporate the manure into the upper 20 cm (8 in) of soil within 1 hour of surface application. The rototiller was used, instead of the tractor-drawn chisel plow used at the field-level, to prevent disruption of the plot frames and of the rainfall simulator setup. Twenty-four hours after the manure was applied, a final rainfall event was conducted to generate 30 minutes of runoff. Simulated rainfall and runoff sampling of manured plots followed protocols described above.

Dissolved reactive P was determined on filtered runoff samples by the colorimetric method of Murphy and Riley (1962). Total P was measured on unfiltered runoff samples by a modified semimicro-Kjeldahl procedure (Bremner 1996). Runoff samples were analyzed for total solids by evaporating 200 mL (7 oz) of unfiltered water in the oven at 70°C (158°F) and weighing the remaining material.

Samples of the Clymer and Wharton soils were obtained from directly next to each plot prior to manure application. Ten samples (0 to 2.5 cm depth [0 to 1 in]) were collected from next to each plot with a stainless steel probe (2.5 cm [1 in] diameter) and combined to form a single composite sample. Samples were air dried and sieved (2 mm [0.08 in]) prior to analysis. Soils were analyzed for Mehlich-3 P (Mehlich 1984) with P determined by colorimetry (Murphy and Riley 1962) and for particle size distribution by the pipette method (Day 1965).

Plot-Scale Integrated Farming System Model Evaluation. The IFSM model simulates and integrates many biological and physical processes in dairy and crop production. The model has been used successfully to compare production options and long-term economic and environmental effects of management changes, including those related to manure application (e.g., Rotz et al. 2002, 2006).

Management practices simulated by IFSM include tillage, manure application, planting, harvesting, and storage operations (Rotz and Coiner 2006). Model input requirements include crop areas, soil characteristics, equipment and structures used, and economic data. Typically the major soil type of the farm is chosen, and fields with the same land use and management practices are lumped together. Spatial relationships of fields and farm structures are not represented in the model. The model simulates the whole-farm annual production scenario over multiple years of weather data to develop a long-term, average annual representation of the environmental and economic conditions of the farm.

Recent updates to soil P processes have improved model predictions of P losses from soil and surface manures (Sedorovich et al. 2007; Vadas et al. 2007) These updates correlated DRP losses to soil P levels and created P pools for manure amended soils. The model simulates decomposition and transformation among four P pools: water-extractable inorganic P, water-extractable organic P, stable inorganic P, and stable organic P. As part of these updates, sediment-bound P losses are computed using an enrichment ratio associated with erosion which, in turn, is predicted by the Modified Universal Soil Loss Equation (Williams 1975).

All treatments in the experimental plot study were simulated in IFSM to predict reductions in DRP and total P loss resulting from immediate incorporation of broadcast manure in a single, representative field on

the farm. To enable comparisons between experimental plot studies and IFSM, the size of the IFSM event-based plot was chosen at the point where modeled and observed sediment concentrations values matched for the pre-manure treatment on a concentration versus area curve. This selection was necessary given that sediment concentration calculations based on sediment loss predicted by the Modified Universal Soil Loss Equation are exponentially dependent on runoff area. That is, holding all other conditions constant, a small increase in area results in a comparatively large increase in sediment concentration for small (<10-ha [25-ac]) areas. For larger areas (>10 ha), the same increase in spatial scale yields a very minimal change in runoff-generated sediment concentrations. The IFSM model was set up to represent a 10-ha field "plot."

The Clymer and Wharton soils were specified as medium sandy loam and medium clay loam, respectively, for IFSM input (table 1). Management and climatic conditions of each soil-treatment combination were replicated as closely as possible in IFSM to evaluate model assessment of surface and broadcast treatments. Manure treatment practices of equivalent impact to the soil surface, as in the plot-level experimentation, were simulated using farm-level machinery. Manure was surface broadcast by a slurry tank spreader at 30 kg total P ha^{-1} (34 lb ac^{-1}). For the incorporation scenarios, the field was tilled by a 3.7-m (12-ft) coulter-chisel plow one day after manure application. Climatic data were adjusted to represent a rainfall event, of the same magnitude as conducted in the plot experiments, occurring directly after manure treatment. To match initial soil hydrologic conditions as closely as possible, the curve number (USDA Soil Conservation Service 1986) for each IFSM representation of a given treatment and soil scenario was back-calculated from measured rainfall and runoff depths for the corresponding experimental plot. Thus, the number of model replications for a given treatment and soil matches that of the observed replications.

Farm-Scale Integrated Farming System Model Application. The event-based, plot-scale experiments and model scenarios highlight an extreme scenario with an intense storm occurring immediately after manure application. To derive long-term trends and effectiveness encountered in realistic conditions, the IFSM model was applied to the farm where the plot experiments were conducted.

Table 1
Properties of Clymer and Wharton soils evaluated in experimental plot studies.

Soil	Texture class	Average slope	Particle size distribution			Mehlich-3 P (mg kg^{-1})
			Sand	Silt	Clay	
Clymer	Medium sandy loam	6%	58%	24%	18%	130
Wharton	Medium clay loam	8%	39%	28%	33%	39

The farm is a dairy operation with 96 Holstein and Guernsey cows and a 185 ha (457 ac) land base of which 157 ha (387 ac) are in cropland and 28 ha (70 ac) in pasture. Crop rotation on the farm, consisting of four years of corn followed by four years of alfalfa hay, provides most of the forage and grain feeds required by the herd. The pasture is grazed over spring, summer, and fall by most cows and half of the heifers. The farm's operators implement no-till planting as a conservation practice; therefore, manure is not typically incorporated into the soil. Dairy slurry is spread prior to growth in the spring, after alfalfa hay cutting during the summer and after fall harvest. Corn receives 34,000 L ha^{-1} (3,600 gal ac^{-1}) slurry during each year of the rotation. Alfalfa hay fields receive approximately 19,000 L ha^{-1} (2,000 gal ac^{-1}) slurry if available after manure is applied to corn fields. No manure is machine-applied to the pasture.

The IFSM model was set up to simulate present conditions at the farm as closely as possible. Model parameters for crop, machinery, harvest, animal, and manure handling processes were derived from data on the farm practices collected from operator interviews and from the farm's nutrient management plan. Wharton clay loam, the dominant soil of the farm, was used in the simulation to allow closer comparison with actual farm data. Two manure management treatment scenarios were developed: broadcast application with no incorporation or tillage and rapid incorporation with a chisel plow. Both treatment scenarios simulated application of dairy manure by splash-plate slurry spreader twice a year: prior to spring planting and after fall harvest. Seventy percent of the manure collected from the herd was applied to the corn land and the remainder went to alfalfa hay land.

Simulations were performed using 25 years of historic weather data from a station near State College, Pennsylvania. The model reinitializes each year so that long-term soil P accumulation and depletion are not determined continuously but as an annual average over the entire period of simulation (Sedorovich et al. 2007). Annual environmental results reflect changes in crop yield, water balance, and P losses due to daily changes in the weather for each year.

Statistical Analyses. Results were analyzed with SAS 8.0 software (SAS Institute Inc., Cary, North Carolina) to derive trends across treatments for the simulated rainfall studies and to compare observed results with predictions using whole farm simulation modeling. Treatment effects were evaluated by Tukey's mean separation technique. The Pearson correlation, r, was used to assess one-to-one linear relationships between rainfall experiment data and event-based modeling predictions. Average annual water quality impacts of surface manure application and incorporation at the farm-level were evaluated by comparing runoff volumes, sediment loss, and P losses across treatments using percent change as a measure of trend. For all variables, differences discussed in the text were considered significant at $\alpha < 0.05$.

Results and Discussion

Rainfall Experiments. Results of the plot experiments, which were designed to maximize the effects of manure management strategies on P losses, revealed significant increases in P concentrations (mg L^{-1}) (table 2) and losses (kg ha^{-1}) (table 3) in runoff with manure application. Manured treatments had total P concentrations in runoff that averaged 6.5 times more than total P in runoff from plots before manure application (table 2), while losses of total P were 4.3 times those before manure application (table 3). For the surface applied manure treatment, these increases likely reflect the enrichment of runoff water with water soluble P in the applied manure (Vadas et al. 2007). For the manure incorporation by tillage treatment, these increases are likely due to the erosion of soil and manure solids. Concentrations and losses of total P in runoff did not differ significantly between the two manure application methods.

Table 2
Average runoff depths and concentrations of dissolved reactive P (DRP), total P, and total solids from experimental plots before and after manure application by two treatment methods.

Soil	Treatment	*N*	Runoff (mm)	DRP (mg L^{-1})	Total P (mg L^{-1})	Total solids (mg L^{-1})
Clymer sandy loam						
	Pre-manure	8	13.80 (7.08)	0.35 (0.14)	0.84 (0.29)	199 (89.85)
	Broadcast	4	4.24 (3.08)	5.39 (3.12)	6.68 (1.86)	755 (285.5)
	Incorporated	3*	9.60 (5.29)	3.38 (0.99)	6.83 (1.51)	650 (207.9)
Wharton clay loam						
	Pre-manure	8	26.69 (2.73)	0.97 (0.13)	1.43 (0.16)	112 (60.0)
	Broadcast	4	23.62 (2.62)	7.78 (0.44)	8.70 (1.48)	493 (370.0)
	Incorporated	4	20.75 (4.22)	0.94 (0.80)	7.45 (3.51)	786 (351.3)

Note: Standard deviations are presented in parentheses.

* One runoff plot did not generate runoff.

Table 3
Average losses of dissolved reactive P (DRP), total P, and total solids from experimental plots before and after manure application by two treatment methods.

Soil	Treatment	*N*	DRP (kg ha^{-1})	Total P (kg ha^{-1})	Total solids (kg ha^{-1})
Clymer sandy loam					
	Pre-manure	8	0.05 (0.03)	0.12 (0.09)	0.03 (0.03)
	Broadcast	4	0.26 (0.33)	0.31 (0.31)	0.04 (0.04)
	Incorporated	3*	0.24 (0.29)	0.46 (0.36)	0.05 (0.04)
Wharton clay loam					
	Pre-manure	8	0.27 (0.26)	0.40 (0.06)	0.03 (0.02)
	Broadcast	4	1.83 (0.18)	2.07 (0.54)	0.12 (0.09)
	Incorporated	4	0.19 (0.16)	1.64 (1.08)	0.17 (0.08)

Note: Standard deviations are presented in parentheses.

* One runoff plot did not generate runoff.

Results of the rainfall experiments were highly influenced by DRP in runoff. Compared with the surface applied manure treatment, incorporating manure into the soil by tillage lowered DRP in runoff an average of 63% by concentration (table 2) and 48% by loss (table 3), although the result varied between soils. This decline in DRP in runoff with tillage has been attributed to removal of water soluble manure P from the soil surface and sorption of that P by soil colloids (Kleinman et al. 2002; Sharpley et al. 2003). Incorporating surface applied manure lowered the proportion of total P in runoff that was dissolved reactive, with an average of 0.85 for surface applied manure to 0.31 for manure that was incorporated with tillage (table 3). Indeed, if one estimates sediment-bound P as the difference between total P and DRP, sediment-bound P concentrations averaged 4.9 times more in runoff from the manured plots that were tilled than those that were not tilled, while sediment-bound P losses were 5.2 times greater.

While runoff P trends were generally consistent between soils, runoff depths were significantly greater from the Wharton soil (averaging 24.44 mm [0.96 in]) than from the Clymer soil (averaging 9.37 mm [0.37 in]), reflecting the finer texture of the Wharton soil (table 2), and hence its lower permeability. Application of manure and its incorporation by tillage did not significantly impact runoff depths from the Wharton soil but did increased rainfall infiltration into the Clymer soil, lowering runoff depths by an average of 50% relative to conditions before manure application (table 2). Results suggest a better potential to manage hydraulic properties of the Clymer soil, at least over the near term. It is possible that surface application of the manure provided a cover that improved rainfall infiltration into the Clymer soil (Unger and Stewart 1983), while tillage increased surface soil porosity and associated moisture storage capacity (Mishra and Singh 2003). Decreases in runoff depths with manure application or with tillage have been documented elsewhere (Mueller et al. 1984; Gilley and Risse 2000). The absence of similar differences in the Wharton soil may be due to the poorer inherent infiltration capacity of that soil, an infiltration capacity that could not be improved by mulching or tillage processes.

Results highlight the interactions of manure management and soil properties on erosion. Total solids concentrations in runoff were significantly greater from the unamended Clymer soil than from the unamended Wharton soil. The concentration of total solids in runoff increased significantly with manure application but did not differ significantly between manure application treatments (table 2). The incorporated manure treatment was expected to yield greater sediment concentrations than the unamended and surface applied manure treatments as a result of increased soil disruption through tillage. The high total solids concentrations in runoff from the surface applied manure treatment were likely associated with readily-detached particles of manure (e.g., organic flocs) that were captured in runoff samples and reflected in measured total solids concentrations. Such losses of light organic matter from manure have been observed elsewhere in rainfall experiment studies on broadcast manure and may be an important contributor to P loss in surface runoff (McDowell and Sharpley

2002; Kleinman and Sharpley 2003). Notably, losses of total solids (table 3) from the Clymer soil did not differ significantly between the three treatments, with greater total solids concentrations of the manure treatments counteracted by the lesser runoff depths observed with these treatments as described above. Losses of total solids from the Wharton soil did, however, reflect the greater concentrations of total solids associated with both of the manure treatments.

Comparison of Experimental Observations with Integrated Farming System Model Predictions. Since the measured precipitation and back-calculated curve numbers were provided as input for event-based IFSM scenarios, observed and predicted runoff depth values were in close agreement for all treatments across both soils (figure 1a). Observed and predicted DRP values, which are closely tied to runoff, were also well correlated with $r = 0.88$ (figure 1b). Visual inspection of the closeness to the one-to-one line showed that the model overestimated DRP for the incorporated scenario for the Wharton clay loam. A variety of factors may have contributed to this discrepancy. Although chisel plow and rototiller are both conservation tillage implements, mixing of manure by rototiller on the small plot into the fine-textured Wharton soil was likely much more effective than would be expected by tractor-drawn tillage practices. In addition, the P transport module in IFSM does not currently account for increased sorption potential of clay soils over sandier soils. This may explain, in part, why modeled DRP to total P concentration ratios are 7 times higher than observed for the incorporated clay loam treatment (table 4). In contrast, modeled concentration ratios for all other treatments range from 0.8 to 1.6 times higher than observed.

The correlation between measured and observed sediment concentrations (figure 1c) was influenced by differences in how the experiment and model quantified total solids. Inspection of the closeness to the one-to-one line suggests that modeled and observed sediment were in reasonable agreement for the pre-manure and incorporated treatments. For the surface applied manure treatment, the model underpredicted loss of total solids. A likely explanation is that IFSM currently predicts only soil particle detachment, using the the Modified Universal Soil Loss Equation equation, while the observed total solids, as discussed earlier, undoubtedly

Figure 1
Comparison of plot experiments and event-based model results, with Pearson correlation coefficients (r) calculated across all soils and treatments ($n = 31$).

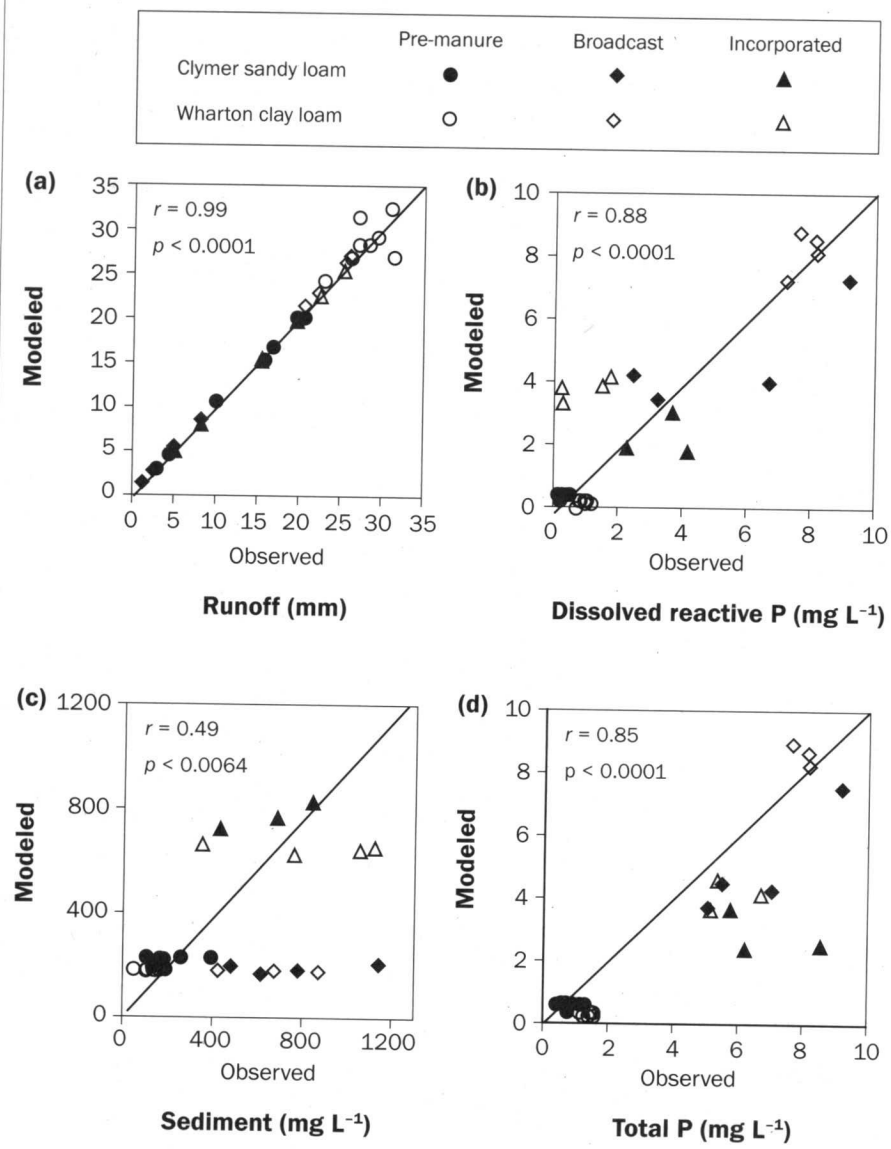


Table 4
Ratios of dissolved reactive P to total P concentrations in runoff for experimental plots and event-based model predictions.

Soil	Treatment	Measured	Predicted
Clymer sandy loam			
	Pre-manure	0.42	0.62
	Broadcast	0.81	0.94
	Incorporated	0.49	0.78
Wharton clay loam			
	Pre-manure	0.68	0.53
	Broadcast	0.89	0.98
	Incorporated	0.13	0.91

Table 5
Comparison of average annual Integrated Farming System Model predictions for two manure management practices (broadcast without incorporation and with incorporation by chisel plow) with expected or actual values for a 185-ha Pennsylvania dairy farm.

	Expected or actual values*	Broadcast (current conditions)	Incorporation
Crop yield			
Corn grain (t DM ha^{-1})	9.5	10.0	7.6
Alfalfa hay (t DM ha^{-1})	6.7	8.5	8.5
Manure properties			
Manure handled (t)	2,452.0	2,569.0	2,569.0
Nitrogen (% DM)	2.7	3.8	3.8
Phosphate (% DM)	1.2	1.2	1.2
Potash (% DM)	2.0	3.6	3.6
Farm P balance			
P import (kg ha^{-1})†	–	8.1	8.1
P export (kg ha^{-1})‡	–	9.4	9.5
P balance§	–	108.0%	109.0%
Runoff (mm)	–	87.2	86.6
Erosion (kg ha^{-1})	–	996.2	1830.7
P loss—leaching (kg ha^{-1})	–	0.02	0.02
Dissolved reactive P—runoff (kg ha^{-1})	–	0.24	0.22
Total P—runoff (kg ha^{-1})	–	0.87	1.23

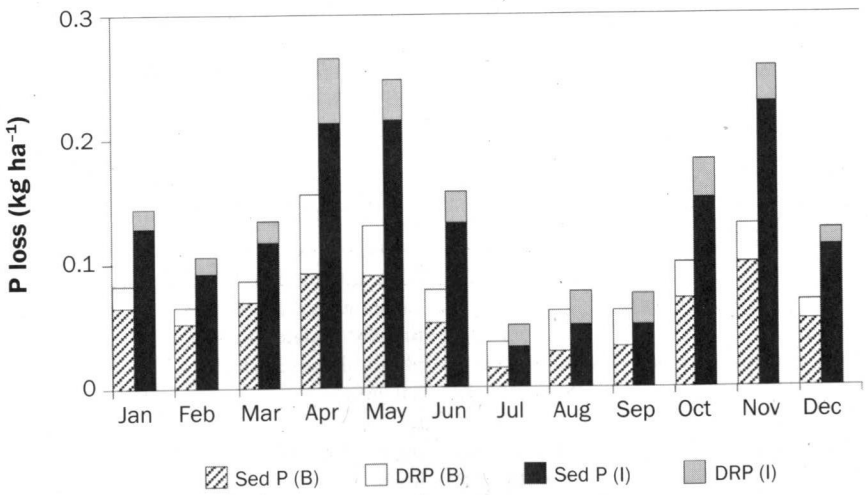
* Values for crop yield and manure production are expected values obtained from the farm's nutrient management plan while manure nutrient contents were determined by standard laboratory analysis.

† Includes P from feed, fertilizer, and deposition.

‡ Includes crop removal.

§ Ratio of nutrients used by crops to that available in the soil.

Figure 2
Average monthly dissolved reactive P (DRP) and sediment-bound P (Sed P) losses obtained through simulation of manure amended cropland on a Pennsylvania dairy farm.



Note: The two scenarios correspond to surface application of manure without incorporation, i.e. broadcast only (B) and with incorporation by chisel-plow (I).

included detached manure particles. This difference is most extreme in the broadcast case where manure was applied without surface disruption, providing slurry to stabilize otherwise loose surface soil particles.

While observed and modeled total P values showed a generally strong correlation (figure 1d) the model underpredicted total P loss. The scenarios where DRP dominated total P were best simulated, such as with surface application of manure to the Wharton clay loam scenario where the observed DRP to total P ratio was 0.89 and the modeled ratio was 0.98. However, the model underpredicted the incorporation treatments, where total P loss was dominated by sediment-bound P. The IFSM's underprediction of sediment-bound P is likely tied directly to its underprediction of sediment.

Whole-Farm Modeling. Average annual crop yield and nutrient values for two 25-year IFSM simulations of the dairy farm, along with expected values, are presented in table 5. Expected values for crop yield and manure production were obtained from the

farmer's nutrient management plan while manure nutrient composition was obtained from standard laboratory analysis. The no-till IFSM scenario reflects current conditions in which manure is broadcast on corn and alfalfa crops twice per year: in the spring prior to corn planting and alfalfa growth and in the fall after corn harvest and alfalfa hay cutting. The IFSM chisel plow scenario represents the farm-level impact of manure incorporation on the corn crops. Matching modeled and expected crop yield is important in accurately estimating crop uptake of nutrients. No yield calibration was explicitly performed as simulated no-till yield values for alfalfa hay and corn grain were close to expected yields. The model predicted that the farm, under current conditions, is in P balance as indicted by the ratio of crop uptake to available P (table 5). Thus, the model and the nutrient management plan for the current conditions both determine farm to be in P balance. Since yield values, manure production, and P manure content are in close agreement to actual or expected values, the model representation was deemed sufficient for determining the relative benefits of manure incorporation, over continued non-incorporation, as a long-term management practice on the farm.

Comparing the farm's current, no-till management with manure incorporation by chisel plow of the 78.5 ha (193.5 ac) in corn in any given year, IFSM predicted equivalent runoff losses but nearly twice the erosion (table 5). Similarly average annual DRP loads decreased minimally with incorporation (3.6 kg [7.9 lb]) while total P loads, which are tied to erosion, increased by 67.2 kg (148.2 lb). Considered only over the land area from which the additional losses occurred (i.e., only the corn land), sediment losses increased by 10.6 kg ha^{-1} (9.5 lb ac^{-1}) while DRP and total P losses increased by 0.05 kg ha^{-1} (0.4 lb ac^{-1}) and 0.86 kg ha^{-1} (0.77 lb ac^{-1}), respectively. Average monthly variations of P losses (figure 2) show that DRP contributed the majority of total P when high runoff events and surface manure application coincided (April). Total P losses with incorporation were consistently higher than without, as expected, due to disruption of the soil by tillage. These losses were largest during months when tillage was performed (April and November); however, the incorporated scenario continued to have higher sediment-bound P losses than the no-till scenario even during summer months of high crop cover.

When the annual percent change in loss due to chisel plow incorporation is averaged over the 25 simulated years of varying weather conditions, the largest increase is in sediment-bound P. Specifically, the model predicts an overall increase in total P load of 36% with incorporation, accompanied by large sediment load increase (77%). The 8% DRP reduction predicted by the farm-scale model does not compensate for the increase in sediment-bound P load. These findings are in agreement with farm-scale modeling by Sedorovich et al. (2007) and with long-term studies into the effects of tillage. In a study of seven dryland watersheds for periods of up to 14 years, Sharpley and Smith (1994) found that sediment and total P losses were on average, 95% and 70% higher respectively, with conventional tillage than with no-till. A 20-year study of clay soil watersheds in the Lake Erie basin found that sediment-bound P accounted for nearly 80% of the total P losses from cropland and that implementation of erosion control practices, including conservation and no-till, lowered total P losses (Baker and Richards 2002). As in the IFSM farm-level simulation, Baker and Richards (2002) also found a tendency of DRP losses to be slightly larger on no-till versus tilled plots; they suggested this was due to buildup of surface-layer soil P.

Summary and Conclusions

Plot-level experiments were designed to evaluate the water quality benefits of implementing rapid manure incorporation as a nutrient conservation practice. The major findings of the plot studies were as follows:

- Immediate incorporation of surface-applied manure decreased measured DRP concentrations an average of 63% in runoff, with the finer clay soil showing greatest impact.
- Sediment-bound P concentrations averaged 4.9 times more in runoff from tilled versus non-tilled treatments.

The IFSM model was configured to simulate manure incorporation scenarios equivalent to those of the plot-level experiments. Integrated Farming System Model predictions agreed with measured DRP concentrations in runoff, supporting the IFSM P module. Expanding the module to improve predictions of P sorption as a function of clay content and tillage practice would likely improve predictions of sediment-bound P. Experimental and model agreement at the plot-level suggested that manure management comparisons under more realistic spatial and temporal farm management conditions might result in similar P reduction efficiencies with manure incorporation.

The IFSM model was applied to a Pennsylvania dairy farm to estimate percentage reduction of edge-of-field P loss resulting from chisel-plow tillage incorporation of surface-broadcast manure on corn fields. The main findings were as follows:

- Manure incorporation through tillage is most beneficial during 'critical' time periods when manure application occurs during wet weather.
- In the long-term the percentage reduction of DRP is likely not as extreme as suggested by single event plot experimentation.
- Increased sediment-bound P and erosion losses associated with tillage reduce the benefits of implementing conservation-tillage incorporation as a P management practice.

Differences between the results obtained from event-based plot experiments and average annual, farm-scale modeling emphasize the need for caution in extrapolating research findings of management practice effectiveness. Single-event rainfall experiments conducted shortly after manure application simulated incidental transfers of soluble P in manure to runoff, resulting in greater losses of DRP. However, the transfer of soluble P in applied manure diminishes with time. Over the annual time frame simulated by whole farm modeling, erosion processes become more important to runoff P losses. Results of this study highlight the need to consider the potential for increased erosion and total P losses caused by soil disturbance during incorporation.

In absence of longer term, field-scale experimental measurements, management practice effectiveness estimates (particularly for P) are, perhaps, most accurately obtained from process-based models. The success of such a suggestion requires models to be continually updated to make use of all available plot-scale research that elucidates individual nutrient responses and interactions due to management practices. However, this suggestion takes advantage of the synergistic knowledge of the model's builders in combining the various model components into a comprehensive representation of the natural system. Thus, such conflicting responses

as reducing runoff P losses or minimizing erosion can be explored, and the findings can be used to aid farm managers and extension personnel in developing field-specific management practice strategies.

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