Estimating Phosphorus Loss in Runoff from Manure and Fertilizer for a Phosphorus Loss Quantification Tool

P. A. Vadas* USDA-ARS
L. W. Good University of Wisconsin–Madison
P. A. Moore Jr. USDA-ARS
N. Widman USDA-NRCS

Nonpoint-source pollution of fresh waters by P is a concern because it contributes to accelerated eutrophication. Given the state of the science concerning agricultural P transport, a simple tool to quantify annual, field-scale P loss is a realistic goal. We developed new methods to predict annual dissolved P loss in runoff from surface-applied manures and fertilizers and validated the methods with data from 21 published field studies. We incorporated these manure and fertilizer P runoff loss methods into an annual, field-scale P loss quantification tool that estimates dissolved and particulate P loss in runoff from soil, manure, fertilizer, and eroded sediment. We validated the P loss tool using independent data from 28 studies that monitored P loss in runoff from a variety of agricultural land uses for at least 1 yr. Results demonstrated (i) that our new methods to estimate P loss from surface manure and fertilizer are an improvement over methods used in existing Indexes, and (ii) that it was possible to reliably quantify annual dissolved, sediment, and total P loss in runoff using relatively simple methods and readily available inputs. Thus, a P loss quantification tool that does not require greater degrees of complexity or input data than existing P Indexes could accurately predict P loss across a variety of management and fertilization practices, soil types, climates, and geographic locations. However, estimates of runoff and erosion are still needed that are accurate to a level appropriate for the intended use of the quantification tool.

Pollution of fresh waters by P is a water quality concern because it contributes to accelerated eutrophication, which limits the use of surface waters for drinking, recreation, and industry (Carpenter et al., 1998; Sharpley and Rekolainen, 1997). Because agriculture is a nonpoint source of P to surface waters (Boesch et al., 2001; Haggard et al., 2005; Johnson et al., 2005; Sigua et al., 2006), there is a need to quickly and accurately identify fields prone to excessive P loss and also management practices to reduce P loss. Process-based simulation models can assess agricultural P loss (Sharpley et al., 2002), but their data and expertise requirements prohibit their use as routine management tools. A simpler approach used throughout the United States and in Europe is a field-scale P Index (Buczko and Kuckenbuch, 2007; Sharpley et al., 2003). However, most P Indexes do not explicitly quantify a mass of P loss (e.g., kg ha^{-1} yr^{-1}). Instead, they use readily obtainable information in an additive and/or multiplicative framework to calculate a qualitative risk of P loss, typically expressed as low, medium, high, or very high. A tool that reliably quantifies field-scale P loss but remains easy to use and requires only readily obtainable inputs is an alternative to process-based models and qualitative P Indexes (Hess et al., 2007).

A field-scale, P loss quantification tool offers attractive characteristics for P loss reduction planning. It could be used in any region where the simulated P loss processes dominate. Because a quantification tool can be formally validated with measured data, it can be designed to accurately account for the relative effect of different management practices on P loss and describe the forms of P lost (i.e., dissolved or sediment-bound). Thus, tradeoffs among various management practices can be assessed, such as the variable effect of no-till management on decreasing sediment P loss but increasing dissolved P loss from surface applications of manure or fertilizer. A quantification tool can provide information about seasonal trends, such as P loss from snow-melt runoff or due to significant precipitation variations. Such information should in-turn drive better management decisions, such as if fall or winter manure application represents the greater risk of P loss given the nature of runoff potential. Fourth, a P loss quantification tool

Copyright © 2009 by the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Published in J. Environ. Qual. 38:1645–1653 (2009).
doi:10.2134/jeq2008.0337
Received 24 July 2008.
*Corresponding author (peter.vadas@ars.usda.gov).
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

P.A. Vadas, USDA-ARS, U.S. Dairy Forage Research Center, 1925 Linden Dr. West, Madison, WI 53706; L.W. Good, 151 Soils Building, 1525 Observatory Dr., Univ. of Wisconsin, Madison, WI 53706; P.A. Moore Jr., USDA-ARS, Room 108 POSC, Univ. of Arkansas, Fayetteville, AR 72701; N. Widman, USDA-NRCS, Room 6158-S, P.O. Box 2890, Washington, DC 20013-2890.

will entail computer automation of inputs and calculations, which offers several opportunities. Soil and climate databases, and erosion, runoff, soil, and crop models can be combined with the P loss tool while still maintaining simple user inputs. This would allow P loss estimation across climate years, crop rotations, or a range of management and fertilization practices. Quantified assessments of the ability of different management practices to decrease P loss could also be linked to optimization programs to design a suite of management practices that balance P loss with other farms goals, such as economic viability. Alternatively, output could be linked to measurable water quality goals (Wisconsin Buffer Initiative, 2005).

For many agricultural fields, the dominant P transport pathway is surface runoff; and the dominant P sources are soil, manure, and fertilizer (Hanson et al., 2002). For these situations, a P loss quantification tool must estimate soil erosion and particulate P loss, runoff, and dissolved P loss from soil, manure, and fertilizer (Lemunyon and Daniel, 2002). Most existing P Indexes already use soil P content as an input and estimate erosion, and existing methods for estimating enrichment ratios can be used to quantify particulate P loss (Sharpley, 1980; Sharpley et al., 2002). The P Indexes that quantify runoff typically use the curve number and annual precipitation (Mallarino et al., 2005; Minnesota P Index Technical Guide, 2006). Loss of dissolved P from soil can be quantified using estimates of runoff, soil P content, and an extraction coefficient, for which data are available (Vadas et al., 2005b). One process that has been a challenge to quantify is dissolved P loss from manure and fertilizer, especially when they are surface-applied and left unincorporated. Our objectives were thus to: (i) develop methods to quantify dissolved P loss in runoff from surface-applied manure and fertilizer, and (ii) to test these methods within one possible framework for an annualized, P loss quantification tool, and (iii) compare the methods with approaches used in existing P Indexes.

Materials and Methods

Quantifying Manure and Fertilizer Phosphorus Runoff

Method Development

We developed methods to estimate annual dissolved P loss from surface manure and fertilizer based on the daily time-step models of Vadas et al. (2007a, 2008). In these models, manure or fertilizer solids are applied and left unincorporated. During a storm, rain releases some manure or fertilizer P from the solids. Released P either infiltrates into soil or is lost in runoff. Runoff dissolved P for a given rain event is calculated as:

$$\text{Runoff Dissolved P} = (\text{Manure or Fertilizer P Released})\ (\text{Runoff/Precipitation})\ (\text{P Distribution Factor}) \quad [1]$$

where:

Runoff Dissolved P: Amount of dissolved P lost in runoff during an event (kg ha^{-1})

Manure or Fertilizer P Released: Amount of dissolved P leached out of manure or fertilizer particles by precipitation during an event (kg ha^{-1})

Runoff: Amount of runoff during an event (mm)

Precipitation: Amount of precipitation during an event (mm)

P Distribution Factor: Empirical factor between 0.0 and 1.0 that distributes released P between runoff and infiltration.

The P Distribution Factor is calculated as:

$$\text{Manure: P Distribution Factor} = (\text{Runoff/Precipitation})^{0.225} \quad [2]$$

$$\text{Fertilizer: P Distribution Factor} = 0.034 \exp\left[(3.4)\ (\text{Runoff/Precipitation})\right] \quad [3]$$

The model assumes that for fertilizer, all applied P is available for release. For manure however, the model assumes water-extractable phosphorus (WEP) is the only source of P released. In this context, Manure WEP is measured by shaking fresh manure with deionized water at a water to solids extraction ratio of 250:1 for 1 h, filtering extracts through 0.45-μm filters, and measuring P in filtrates (Vadas et al., 2004). Manure WEP is commonly estimated at extraction ratios other than 250:1. For example, the Arkansas pasture P Index uses manure WEP to estimate field-scale, annual P loss, but bases WEP values on a 10:1 extraction ratio. However, data generated from other extraction ratios can be converted to a 250:1 equivalent using relationships from Vadas et al. (2005a).

In the models of Vadas et al. (2007a, 2008), only a portion of manure WEP or fertilizer P is released during a storm; and manure or fertilizer P loss in runoff over several months or a year is the sum of P loss for all individual storms. Our model estimates that typical manure application rates of 4 to 9 Mg ha^{-1} would require about 25 to 50 cm of cumulative precipitation for all manure WEP to be released. In most U.S. regions, annual precipitation should thus be sufficient to release all applied manure WEP or fertilizer P (Vadas et al., 2007b). Thus, we adapted Eq. [1] to estimate annual manure or fertilizer dissolved P loss in runoff as:

$$\text{Manure Runoff P} = (\text{Manure WEP Applied})\ (\text{Annual Runoff/Precipitation})\ (\text{P Distribution Factor}) \quad [4]$$

$$\text{Fertilizer Runoff P} = (\text{Fertilizer P Applied})\ (\text{Annual Runoff/Precipitation})\ (\text{P Distribution Factor}) \quad [5]$$

where:

Manure WEP: Amount of water extractable P applied in manure (kg ha^{-1})

Fertilizer P: Amount of total fertilizer P applied (kg ha^{-1})

The P Distribution Factors are calculated as in Eq. [2] and [3], except using cumulative runoff and precipitation (rain+snow) values for an entire year. Based on limited data of Vadas (2006), our model assumes that for liquid manures (i.e., solids content less than ~15%), 60% of applied manure WEP infiltrates into soil at application and becomes unavailable for direct loss in runoff. This 60% is not included in Eq. [4]. The term Annual in Eq. [4] and [5] can refer to any 12-mo period, not just a calendar year. Only highly soluble fertilizers such as triple superphosphate or ammonium phosphates are considered here. We do not consider less soluble fertilizers such as rock phosphate or partially acidulated phosphates.

Method Validation

We tested our manure and fertilizer P runoff quantification methods with data from 21 studies (Table 1) where manure or fertilizer was surface-applied and left unincorporated to areas ranging from 1 m^2 to 4.5 ha. None of these data were used in the development of Eq. [1] to [5]. Runoff was collected for periods ranging from 60 to 180 d after application. Twelve studies collected runoff from natural storms, while nine used simulated rain experiments. All studies reported total cumulative rain, runoff, and dissolved P loss for the entire monitoring period. Fertilizer studies reported total fertilizer P applied, and manure studies reported either total manure mass or total manure P applied. When needed, we estimated total manure P and manure WEP applied based on manure P concentrations reported in a survey of manure P characteristics (Kleinman et al., 2005). While manure P content can vary widely based on feeding, storage, and handling practices, reliable model predictions (discussed below) demonstrate that the manure P estimates we used were reasonable. We used Eq. [2] to [5] to quantify dissolved P loss in runoff for the entire monitoring period. In Eq. [4] and [5], we used reported runoff and precipitation for only the monitoring period and not the entire calendar year when monitoring occurred.

Validation results in Fig. 1a show we were able to accurately quantify dissolved P loss in runoff from fertilizers. An analysis using the PROC REG function in SAS (SAS Institute, 1999) showed the slope and intercept of the regression line relating predicted and measured values were not different (P = 0.05) from unity or zero. We also calculated a Nash Sutcliffe model efficiency of 0.87 (Nash and Sutcliffe, 1970). Nash-Sutcliffe efficiencies can range from $-\infty$ to 1. An efficiency of 1 corresponds to a perfect match of modeled and observed data. An efficiency of 0 indicates model predictions are as accurate as the mean of observed data, and an efficiency less than zero occurs when the observed mean is a better predictor than the model. The closer the model efficiency is to 1, the more accurate the model.

For manure data, we calculated a Nash Sutcliffe model efficiency of 0.91. While the intercept (–0.03) of the regression line relating predicted and measured values was not different from zero, the regression slope (0.87) was less than one (data not shown). This under-prediction is likely because we used only applied manure WEP in Eq. [4]. This did not account for manure P that was in non-WEP forms at application but subsequently mineralized to WEP and was lost in runoff during the monitoring period (McGrath et al., 2005; Vadas et al., 2007b; Warren et al., 2008). Using the manure P and runoff model of Vadas et al. (2007a), we estimated about 10% of manure non-WEP mineralizes to WEP during the time periods of the 12 studies (up to 180 d, Table 1). Accounting for manure non-WEP mineralization to WEP changes Eq. [4] to:

$$\text{Manure Runoff P} = (\text{Manure WEP Applied} + \text{Manure non-WEP mineralized})\,(\text{Annual Runoff/Precipitation})\,(\text{P Distribution Factor}) \quad [6]$$

where:

Manure non-WEP mineralized: Amount of manure P transformed from non-WEP forms to a WEP form during a specified time period (kg ha^{-1}).

Table 1. Studies used to validate our method of predicting dissolved P loss in runoff from surface manure and fertilizer.

Source	Location	Plot size	Crop	Monitoring duration	Total P applied	Available manure WEP†	Total rain	Total runoff	Soil test P
		m^2		d	kg ha^{-1}	kg ha^{-1}	mm	mm	mg kg^{-1}
Manure									
Edwards and Daniel (1994)	AR	9	Grass	70	87.4	28.4	482	30.4	NR‡
Gaudreau et al. (2002)	TX	6	Grass	60 to 90	50–100	7.5–15	177–308	87–99	45
Klausner et al. (1976)	NY	3200	Fallow	90	28–168	14–84	154–175	1–16	NR
Mueller et al. (1984)	WI	1.35	Corn	90 to 120	40	22	290–435	19–34	NR
Reese et al. (1982)	SC	120	Grass	60	94–142	52–78	150	33	NR
Schroeder et al. (2004)	GA	2	Grass	150	21–142	7–45	485–540	90–195	22
Shah et al. (2004)	WV	5.9	Grass	150	50	12.5	585	51	9
Smith et al. (2001)	UK	30	Wheat	120 to 180	16–81	9–20	100–250	3–19	NR
Vadas et al. (2007b)	PA	0.9	Fallow	150	190–640	43–157	1100	42	40
Withers and Bailey (2003)	UK	30	Fallow	40 to 110	13–31	4–10	157–334	1–64	50
Withers et al. (2001)	UK	32	Wheat	80 to 110	37–60	12–20	90–159	1–13	20
Young and Mutchler (1976)	MN	100	Alfalfa, corn	150	15–114	7–29	135–190	3–112	NR
Fertilizer									
Edwards and Daniel (1994)	AR	9	Grass	70	87.4	–	482	30.4	NR
Gaudreau et al. (2002)	TX	6	Grass	60 to 90	25–50	–	177–309	87–99	45
McDowell and Catto (2005)	New Zealand	0.2	Grass	190	30	–	116	95	13
McDowell et al. (2003)	New Zealand	0.2	Grass	180	18–32	–	225	184	35
Nicholaichuk and Read (1978)	Canada	45,000	Wheat	180	54	–	136	7–49	25
Seo et al. (2005)	TN	158	Residue	90	51	–	379–488	5–17	17
Shigaki et al. (2006)	PA	2	Grass, corn	45	100	–	66–85	34–38	60
Shigaki et al. (2007)	PA	0.2	Grass	60	100	–	150	50–87	70
Withers et al. (2001)	UK	32	Bare	80 to 110	60–90	–	92–159	1–5	20

† WEP, water extractable phosphorus.

‡ NR, not reported.

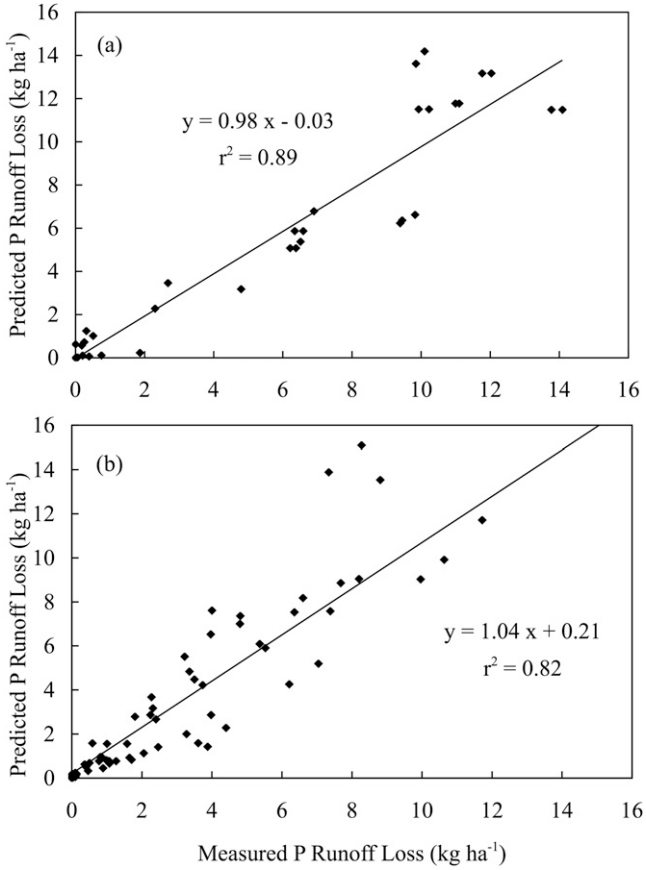

Fig. 1. Measured and predicted dissolved runoff P loss for 21 published studies using (a) surface-applied fertilizers, and (b) surface-applied manures, where manure non-water extractable phosphorus (WEP) mineralization is considered in predictions.

Accounting for manure non-WEP mineralization resulted in accurate estimates of dissolved P loss, with the regression line intercept and slope not significantly different from zero or one and a Nash Sutcliffe model efficiency of 0.82 (Fig. 1b).

Figure 1 results show our simple equations can accurately quantify cumulative dissolved P loss in runoff over several months for a variety of field sizes, crop and manure management conditions, manure types, and geographic locations. Because data represent periods less than 12 mo, Eq. [4] and [5] could be applied on a seasonal basis (i.e., 3–4 mo) instead of an annual basis, given that enough precipitation falls within that season to remove all WEP from manure. Seasonal predictions may indeed be more appropriate for locations where runoff/precipitation ratios vary significantly throughout the year.

Annual Phosphorus Loss Quantification Tool

Quantification Tool Development

Our second objective was to test our manure and fertilizer P loss quantification methods within one possible framework of an annualized, P loss quantification tool. The tool presented here is not intended to represent a final P loss prediction tool that is universally applicable across all geographic locations. Instead, we developed a framework for a tool that could be used for fields where surface runoff is the dominant P loss pathway and total P loss is dominated by sediment P loss from eroded soil and dissolved P loss from soil, manure, and fertilizer. We collected rain, runoff, erosion, soil P, manure or fertilizer application, and field management data from 28 published studies (independent of those in Table 1) that monitored P loss in runoff for at least 1 yr (Table 2). Studies represented a variety of tillage and cropping practices, manure and fertilizer types and application methods, and geographic locations, including Ireland and Australia.

We estimated sediment P loss in runoff as:

$$\text{Sediment P Loss} = (\text{eroded sediment})\ (\text{soil total P})\ (\text{P Enrichment Ratio})/(1 \times 10^6) \quad [7]$$

where:

Sediment P Loss: Annual P loss in runoff associated with eroded sediment (kg ha^{-1})

Eroded Sediment: Annual soil lost in runoff due to erosion (kg ha^{-1})

Soil Total P: Total P content of surface soil (mg kg^{-1})

P Enrichment Ratio: Unitless ratio of total P in eroded sediment to that in the source soil

We used reported data for eroded sediment. We calculated the P Enrichment Ratio based on equations from Menzel (1980) and Sharpley (1980):

$$\ln(\text{P Enrichment Ratio}) = 2.2 - 0.25 \ln(\text{eroded sediment}) \quad [8]$$

For soil total P in Eq. [7], we either used reported data or estimated soil total P from reported soil characterization data with an equation currently used in the Wisconsin P Index:

$$\text{Soil Total P} = [13 + (27 \times \text{Soil OM}) + (0.06 \times \text{Soil Labile P})]^2 \quad [9]$$

where:

Soil OM: Organic matter content of the surface soil (g kg^{-1})

Labile P: Soil Labile P content of the surface soil (mg kg^{-1})

We estimated Labile P from reported soil test P, assuming Labile P is the same as Olsen P and Mehlich-1 P, and half of Mehlich-3 P and Bray-1 P (Sharpley et al., 1989; Vadas et al., 2006).

To estimate dissolved inorganic P loss in runoff from soil, we used the equation of Vadas et al. (2005b):

$$\text{Dissolved Soil Runoff P} = (\text{Soil Labile P})\ (0.004)\ (\text{Annual Runoff})\ (0.1) \quad [10]$$

where:

Dissolved Soil Runoff P: Annual amount of dissolved P lost in runoff (kg ha^{-1})

We used values for Labile P (mg kg^{-1}) estimated as above and reported values for runoff (cm). The 0.004 value is an extraction coefficient that estimates dissolved P in runoff (mg L^{-1}) from soil Labile P, and 0.1 ensures kg ha^{-1} units for Dissolved Soil Runoff P. We used Eq. [5] and [6] to estimate dissolved P loss from surface manure or fertilizer. We also made the following calculations in the model:

Table 2. Studies used to validate our annual runoff P loss quantification tool.

Source	Location	Plot size	Crop	Duration	P Source	Runoff measurements
		ha		mo		
Angle et al. (1984)	MD	0.26–0.37	Corn	36	Dairy manure	Erosion, dissolved P, total P
Berg et al. (1988)	OK	2.7–5.6	Grassed, wheat	120	None	Erosion, dissolved P, total P
Burwell et al. (1975)	MN	0.009	Corn, oats, hay	72	Fertilizer	Erosion, dissolved P, total P
Cabot et al. (2006)	WI	0.01–0.03	Alfalfa	12	Dairy manure	Erosion, dissolved P, total P
Chinkuyu et al. (2002)	IA	0.4	Corn, soybean	36	Hen manure	Dissolved P
Edwards et al. (1996)	AR	0.57–1.46	Grassed	30	Poultry litter, grazing manure	Dissolved P
Gessel et al. (2004)	MN	0.007	Corn, soybean	36	Swine manure	Erosion, dissolved P, total P
Ginting et al. (1998)	MN	0.007	Corn	24	Beef manure	Erosion, dissolved P, total P
Harmel et al. (2004)	TX	1.2–8.4	Corn, pasture	36	Poultry litter, grazing manure	Erosion, sediment P, dissolved P
Jones et al. (1985)	TX	2.1–3.3	Grassed	72	None	Erosion, total P
Kurz et al. (2005)	Ireland	0.46–1.54	Grassed	15	Fertilizer, grazing manure	Dissolved P
Langdale et al. (1985)	GA	1.3–2.7	Corn, rye	12	Fertilizer	Erosion, sediment P, dissolved P
McDowell and McGregor (1980)	MS	0.01	Corn, soybean	18	Fertilizer	Erosion, dissolved P, total P
Moore and Edwards (2007)	AR	0.41	Pasture	120	Poultry Litter	Dissolved P
Owens and Shipitalo (2006)	OH	2.2–4.2	Pasture	132	Fertilizer, grazing cow manure	Dissolved P
Panuska et al. (2008)	WI	0.0146	Corn	12	Liquid dairy manure	Erosion, total P, dissolved P
Pierson et al. (2001)	GA	0.75	Pasture	36	Poultry litter, grazing manure	Dissolved P
Sistani et al. (2008)	MS	0.1 to 0.7	Pasture	24	Poultry litter, grazing manure	Erosion, total P
Smith and Monaghan (2003)	Australia	0.05–0.09	Pasture	36	Grazing cow manure	Erosion, dissolved P, total P
Soileau et al. (1994)	AL	3.8	Cotton, rye	72	Fertilizer	Erosion, dissolved P, sediment P
Thoma et al. (2005)	MN	0.016	Corn	38	Swine manure, fertilizer	Erosion, dissolved P, total P
Vervoort et al. (1998)	GA	0.45	Grassed	30	Poultry litter	Dissolved P
Vories et al. (2001)	AR	0.6	Cotton	36	Poultry litter	Erosion, total P, dissolved P
Westerman et al. (1985)	NC	0.008	Grassed	72	Swine manure	Total P
Westerman et al. (1987)	NC	0.008	Grassed	48	Swine manure	Total P
Wood et al. (1999)	AL	0.001	Corn, rye	24	Fertilizer, poultry litter	Erosion, sediment P, dissolved P
Wortmann and Walters (2006)	NE	0.004	Corn, soybean	36	Composted beef manure	Erosion, dissolved P, total P
Young and Holt (1977)	MN	0.001	Alfalfa, corn	36	Fertilizer, dairy manure	Erosion, dissolved P, total P

1. When manure or fertilizer was tilled into soil, we estimated the portion of applied P mixed into the soil (and thus unavailable for direct loss in runoff) based on tillage equipment as reported used and associated incorporation efficiency values (Stott et al., 1995).
2. For manure on the soil surface, 20% of non-WEP mineralized into WEP based on the daily manure P model of Vadas et al. (2007a) to satisfy Eq. [6]. For spring-applied manure, 15% of manure non-WEP mineralized the same calendar year of application and 5% the following year. For fall-applied manure, 5% of non-WEP mineralized the same calendar year of application and 15% the following year.
3. For fall-applied manure, 75% of Manure WEP Applied in Eq. [6] was lost in runoff the same calendar year of application and 25% the following year.
4. The non-WEP mineralization rate for alum-treated poultry litter was 1/10 of that for untreated litter (Warren et al., 2008).
5. For studies with grazing cattle (*Bos taurus*), we used reported number of cows and grazing times to calculate cow grazing days per year. We assumed a beef cow produces 2.9 kg and a dairy cow produces 5.4 kg dry weight of feces daily; beef cow feces is 1.1% and dairy cow feces is 0.78% total P; feces WEP at deposition is 55% of total P (Vadas et al., 2007a).
6. Total manure WEP (both applied and mineralized, kg ha^{-1}) not lost in runoff was either tilled or infiltrated into soil and increased soil Labile P as:

$$\text{Labile P Increase} = (\text{Total Manure WEP} - \text{Manure WEP in Runoff})\ (\text{PSC})\ (10)/(\text{BD})/(\text{Depth}) \quad [11]$$

where:

Labile P Increase: Amount that soil labile P increases due to P addition from manure (mg kg^{-1})

Total Manure WEP: Sum of manure WEP applied and manure P mineralized to WEP (kg ha^{-1})

Manure WEP in Runoff: Annual amount of manure WEP lost in runoff (kg ha^{-1})

BD: soil bulk density (Mg m^{-3})

Depth: The depth of soil affected by manure P (cm)

PSC: P Sorption Coefficient, unitless value between zero and one representing how much P added to a soil remains labile.

We assumed bulk density at 1.2 Mg m^{-3}. For grassed or no-till soils, we assumed Depth was 2.5 cm (Vadas et al., 2007a, 2007b). For tilled soils, we assumed a Depth of 15 cm. We assumed applied fertilizer P not lost in runoff similarly increased Labile P. We estimated PSC values from reported soil proper-

ties using equations developed from data of 78 U.S. soils by Sharpley et al. (1984).

Phosphorus Loss Quantification Tool Validation

Results in Fig. 2 show our P loss tool reliably quantified annual dissolved P loss in runoff. The slope and intercept of the regression line for predicted and measured values were not significantly different ($P = 0.05$) from unity or zero. We also calculated a Nash Sutcliffe model efficiency of 0.77. Data represent 24 studies from 13 different states, Australia, and Ireland where fertilizer, manure, and soil all contributed to dissolved P loss in runoff, where applied manure was both incorporated and unincorporated, and manure sources included both machine-applied manure and manure from grazing cattle. These validation data also include data used by DeLaune et al. (2004) in validating the Arkansas pasture P Index, which demonstrates the applicability of our tool to pastures as well as cropped land.

Figure 3 shows results for measured and predicted annual sediment P loss in runoff from four studies in Texas, Alabama, Minnesota, and Wisconsin. While the slope of the regression line relating predicted and measured values was not significantly different ($P = 0.05$) from unity, the intercept was somewhat greater than zero. However, a Nash Sutcliffe model efficiency of 0.87 indicates our tool still reliably quantified annual sediment P loss in runoff. Thus, our methods of estimating soil total P content (Eq. [9]) and a P enrichment ratio (Eq. [8]) can reliably quantify sediment P loss for the variety of management practices, soil types, and geographic locations represented in these studies. Figure 4 shows model results for annual total P loss in runoff from 19 studies from 11 states and Australia. Data represent a combination of particulate P loss and dissolved P loss from soil, fertilizer, and manure. A regression slope and intercept not significantly different ($P = 0.05$) from unity or zero and a Nash Sutcliffe efficiency of 0.89 all indicate our tool reliably quantified annual total P loss in runoff.

Our results demonstrate that if reliable estimates of soil erosion and runoff are available, fairly simple equations can be used to accurately quantify annual, field-scale P loss in runoff for the wide variety of soil types, climates, management practices, and geographic locations represented in the investigated studies. Table 3 shows results for a sensitivity analysis for the major model input variables, which were fertilizer P applied, manure WEP available for loss in runoff, soil labile P, soil total P, annual eroded sediment, annual precipitation, and annual runoff. Annual P loss estimates were least sensitive to variables concerning the sources of dissolved P loss (fertilizer P, manure WEP, and soil Labile P). Model estimates were more sensitive to variables concerning sediment-bound P loss (annual eroded sediment and soil total P), but were most sensitive to the variables concerning P transport (precipitation and runoff). The input variables for fertilizer P, manure WEP, soil Labile P, soil total P, and annual precipitation can all be measured, which suggests they should not introduce high degrees of uncertainty into P loss estimates. Only the variables for runoff and eroded sediment will have to be estimated.

Estimating field-scale runoff and erosion is not trivial, even for a P loss tool that does not necessarily need to predict high degrees of spatial and temporal rain and runoff variability. Existing P Indexes typically use RUSLE (Renard et al., 1997) or RUSLE2 (Foster et al., 2000) to estimate annual erosion, and adaptations of the curve number method (National Resource Conservation Service, 2004) with annual precipitation to estimate runoff. We assume these methods would also be used to implement a P loss quantification tool such as ours. These erosion and runoff prediction tools rely on long-term, average annual weather in their calculations and are not designed to predict year-to-year weather, erosion, and runoff variability. Therefore, it is difficult at times to validate RUSLE or the curve number with just a few years of monitoring data (Harmel et al., 2005). However, because they are widely accepted, well-supported, state-of-the-art planning tools that represent decades of data and development, planners find them appropriate and valuable for decision-support tools used to help reduce field-scale P loss.

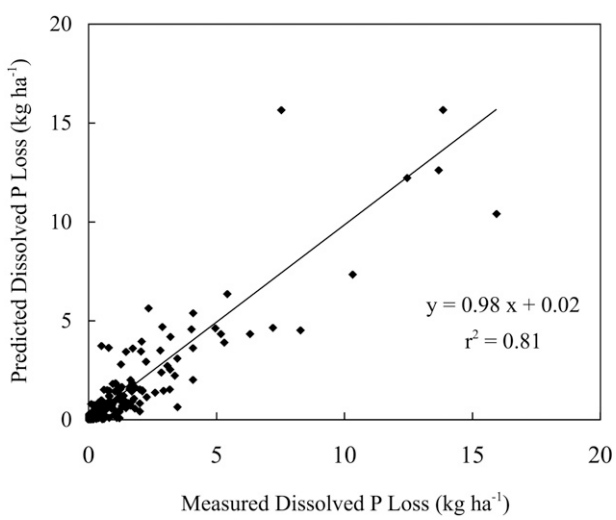

Fig. 2. Measured and predicted annual dissolved P loss in runoff from 22 published studies.

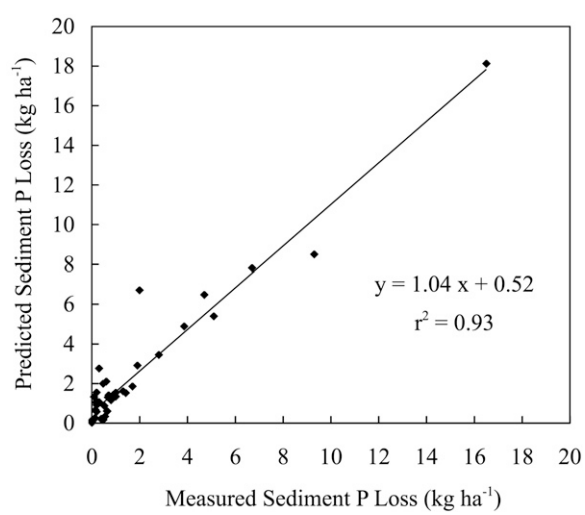

Fig. 3. Measured and predicted annual sediment P loss in runoff from four published studies.

Comparison with Existing Phosphorus Loss Quantification Methods

Phosphorus Indexes using methods similar to the ones presented here to quantify annual, field runoff P have been developed in Arkansas, Iowa, Minnesota, Missouri, North Carolina, and Wisconsin. Validation studies of these Indexes generally show good relationships between measured P loss and P Index values (Bundy et al., 2008; DeLaune et al., 2004; Minnesota P Index Technical Guide, 2006), but these validation studies are limited. Our new methods for estimating dissolved P loss in runoff from surface manures and fertilizers have recently been incorporated into the Wisconsin P Index (Good and Panuska, 2008). The old version of the Wisconsin P Index as well as the existing Iowa and Minnesota P Indexes (Mallarino et al., 2005; Minnesota P Index Technical Guide; 2005) all quantify dissolved P loss from surface manure and fertilizer with equations to which we could readily apply the data from 22 published studies in Table 2. The Minnesota Index and old Wisconsin Index both assume a percentage of surface applied manure and fertilizer P is lost in runoff. The Minnesota Index sets this at a constant 3%, while the old Wisconsin Index varies the percentage from 0.5 to 4% depending on the season of application. The Iowa Index accounts for surface manure and fertilizer P loss by assessing the influence of these P sources on soil P and estimating P loss in a manner similar to that for soil P. For all three Indexes, we used measured runoff data and Index equations to estimate dissolved P loss from soil, manure, and fertilizer. By comparing results with our results in Fig. 2, we could thus assess if our approach for estimating dissolved P loss from surface manure and fertilizer represents an improvement over some existing approaches. Because the Iowa and Minnesota Indexes were developed for specific soil and climate conditions in those states, this comparison was intended to assess only the relative results of our methods and these other approaches and not their ability to estimate P loss for conditions outside of Iowa and Minnesota.

Table 4 presents regression equations for measured and estimated dissolved P loss for our methods and the other existing approaches. The approach used in the Iowa Index poorly quantified dissolved P loss. The approach used in the Minnesota and old Wisconsin Indexes produced good correlations between measured and predicted dissolved P, but with the Minnesota Index generating greater estimates. However, our new methods for estimating dissolved P loss from surface manure and fertilizer provided the most accurate estimates.

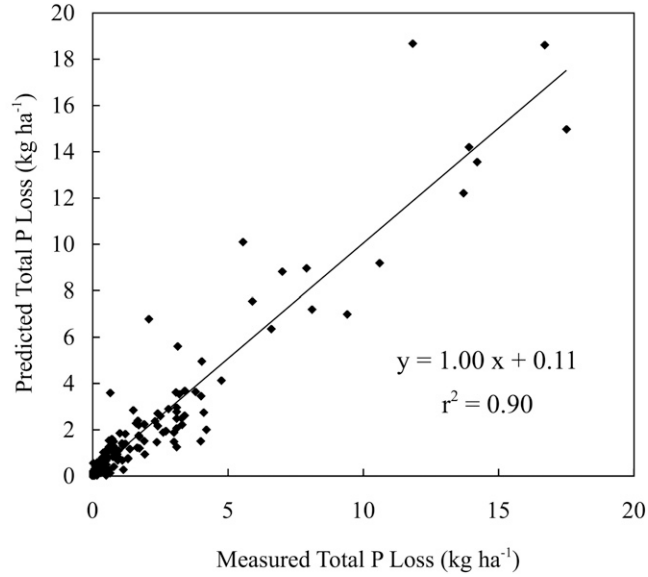

Fig. 4. Measured and predicted annual total P loss in runoff from 16 published studies.

Summary

Our results show that our new methods to estimate P loss in runoff from surface manure and fertilizer are an improvement over methods used in existing Indexes, and that it is possible to reliably quantify annual, field-scale dissolved, sediment, and total P loss in runoff using simple methods and readily obtainable inputs, especially if sufficiently accurate estimates of runoff and erosion are available. Thus, a runoff P loss quantification tool does not necessarily require more complex input than existing P Indexes. The same tool can reliably quantify P loss across a variety of management and fertilization practices, soil types, climates, and geographic locations. However, developing a single, P loss quantification tool that can be used across an eco-region will be a challenge, especially given the need to adequately simulate runoff, erosion, or other pathways of P loss (i.e., subsurface transport in groundwater or through drainage networks). To allow the use of this tool in planning watershed-level water quality programs, other issues related to spatial representation or estimating P delivery from fields to water bodies must also be addressed.

References

Angle, J.S., G. McClung, M.S. McIntosh, P.M. Thomas, and D.C. Wolf. 1984. Nutrient losses in runoff from conventional and no-till corn watersheds.

Table 3. Results of a sensitivity analysis of the major input variables for our P loss quantification tool. Input variable values were changed by +10%,-10%, +25%, and -25%.

	Percent change in total P loss prediction							
	+10%		−10%		+25%		−25%	
Input variable	Avg.	Maximum	Avg.	Maximum	Avg.	Maximum	Avg.	Maximum
Fertilizer P Added	0.8	7.7	−0.8	−7.7	2.1	19.3	−2.1	−19.3
Soil labile P	1.4	8.1	−1.4	−8.1	3.6	20.3	−3.6	−20.3
Manure WEP available	1.7	9.7	−1.7	−9.7	4.3	24.4	−4.3	−24.4
Annual eroded sediment	3.3	9.8	−3.3	−9.8	8.0	24.5	−8.0	−24.5
Soil total P	4.4	10.0	−4.4	−10.0	10.9	25.0	−10.9	−25.0
Annual precipitation	−4.7	−12.3	5.9	16.4	−10.1	−25.8	18.1	54.5
Annual runoff	6.7	15.6	−6.5	−14.4	17.0	41.6	−16.1	−33.8

Table 4. Regression equations relating measured P loss data from the 22 studies in Table 2 and predicted data from our P loss quantification tool, the Iowa P Index, the Minnesota P Index, and the former version of the Wisconsin P Index.

P Loss quantification method and category	Regression equation
New methods	Predicted P loss = (0.98) (Measured P Loss) + 0.02 r^2 = 0.81
Iowa P Index	Predicted P loss = (0.01) (Measured P Loss) + 0.03 r^2 = 0.20
Minnesota P Index	Predicted P loss = (3.59) (Measured P Loss) + 0.78 r^2 = 0.71
Old Wisconsin P Index	Predicted P loss = (1.07) (Measured P Loss) + 0.84 r^2 = 0.60

J. Environ. Qual. 13:431–435.

Berg, W.A., S.J. Smith, and G.A. Coleman. 1988. Management effects on runoff, soil, and nutrient losses from highly erodible soils in the southern plains. J. Soil Water Conserv. 43:407–410.

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. 2001. Chesapeake Bay eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. J. Environ. Qual. 30:303–320.

Buczko, U., and R.O. Kuckenbuch. 2007. Phosphorus indices as risk-assessment tools in the USA and Europe–A review. J. Plant Nutr. Soil Sci. 170:445–460.

Bundy, L.G., A.P. Mallarino, and L.W. Good. 2008. Field scale tools for reducing nutrient loss to water resources. Available at http://wpindex.soils.wisc.edu/assets/FieldScaleTools.pdf (verified 4 May 2009). Univ. of Wisconsin, Madison.

Burwell, R.E., D.R. Timmons, and R.F. Holt. 1975. Nutrient transport in surface runoff as influenced by soil cover and seasonal periods. Soil Sci. Soc. Am. Proc. 39:523–528.

Cabot, P.E., K.G. Karthikeyan, P.S. Miller, and P. Nowak. 2006. Sediment and phosphorus delivery from alfalfa swards. Trans. ASABE 49:375–388.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl. 8:559–568.

Chinkuyu, A.J., R.S. Kanwar, J.C. Lorimor, H. Xin, and T.B. Bailey. 2002. Effects of laying hen manure application rate on water quality. Trans. ASAE 45:299–308.

DeLaune, P.B., P.A. Moore, Jr., D.K. Carman, A.N. Sharpley, B.E. Haggard, and T.C. Daniel. 2004. Evaluation of phosphorus source component in the phosphorus index for pastures. J. Environ. Qual. 33:2192–2200.

Edwards, D.R., and T.C. Daniel. 1994. Quality of runoff from fescuegrass plots treated with poultry litter and inorganic fertilizer. J. Environ. Qual. 23:579–584.

Edwards, D.R., T.C. Daniel, J.F. Murdoch, and P.A. Moore, Jr. 1996. Quality of runoff from four northwest Arkansas pasture field treated with organic and inorganic fertilizer. Trans. ASAE 39:1689–1696.

Foster, G.R., D.C. Yoder, D.K. McCool, G.A. Weesies, T.J. Toy, and L.E. Wagner. 2000. Improvements in science in RUSLE2. ASAE Paper 00–2147. ASAE, St. Joseph, MI.

Gaudreau, J.E., D.M. Vietor, R.H. White, T.L. Provin, and C.L. Minster. 2002. Response of turf and quality of runoff water to manure and fertilizer. J. Environ. Qual. 31:1316–1322.

Gessel, P.D., N.C. Hansen, J.F. Moncrief, and M.A. Schmitt. 2004. Rate of fall-applied liquid swine manure: Effects on runoff transport of sediment and phosphorus. J. Environ. Qual. 33:1839–1844.

Ginting, D., J.F. Moncrief, S.C. Gupta, and S.D. Evans. 1998. Corn yield, runoff, and sediment losses from manure and tillage systems. J. Environ. Qual. 27:1396–1402.

Good, L.W., and J.C. Panuska. 2008. Current calculations in the Wisconsin P Index. Available at http://wpindex.soils.wisc.edu/assets/PIndexCalculationsDec08.pdf (verified 1 May 2009). University of Wisconsin, Madison.

Haggard, B.E., P.A. Moore, Jr., and P.B. DeLaune. 2005. Phosphorus flux from bottom sediments in Lake Eucha, Oklahoma. J. Environ. Qual. 34:724–728.

Hanson, N.C., T.C. Daniel, A.N. Sharpley, and J.L. Lemunyon. 2002. The fate and transport of phosphorus in agricultural systems. J. Soil Water Conserv. 57:408–417.

Harmel, R.D., H.A. Torbert, P.B. DeLaune, B.E. Haggard, and R.L. Haney. 2005. Field evaluation of three phosphorus indices on new application sites in Texas. J. Soil Water Conserv. 60:29–42.

Harmel, R.D., H.A. Torbert, B.E. Haggard, R. Haney, and M. Dozier. 2004. Water quality impacts of converting to a poultry liter fertilization strategy. J. Environ. Qual. 33:2229–2242.

Hess, P., B. Eisenhauer, and B. Joern. 2007. Challenges to using and implementing phosphorus indices in nutrient management planning: An NMP perspective. p. 333–349. *In* D.E Radcliffe and M.L. Cabrera (ed.) Modeling phosphorus in the environment. CRC Press, Boca Raton, FL.

Johnson, A.M., D.L. Osmond, and S.C. Hodges. 2005. Predicted impact and evaluation of North Carolina's phosphorus indexing tool. J. Environ. Qual. 34:1801–1810.

Jones, O.R., H.V. Eck, S.J. Smith, G.A. Coleman, and V.L. Hausner. 1985. Runoff, soil, and nutrient losses from rangeland and dry-farmed cropland in the southern high plains. J. Soil Water Conserv. 40:161–164.

Klausner, S.D., P.J. Zwerman, and D.F. Ellis. 1976. Nitrogen and phosphorus losses from winter disposal of dairy manure. J. Environ. Qual. 5:47–49.

Kleinman, P.J.A., A.M. Wolf, A.N. Sharpley, D.B. Beegle, and L.S. Saporito. 2005. Survey of water-extractable phosphorus in livestock manures. J. Environ. Qual. 69:701–708.

Kurz, I., C. Coxon, H. Tunney, and D. Ryan. 2005. Effects of grassland management practices and environmental conditions on nutrient concentrations in overland flow. J. Hydrol. 304:35–50.

Langdale, G.W., R.A. Leonard, and A.W. Thomas. 1985. Conservation practice effects on phosphorus losses from southern piedmont watersheds. J. Soil Water Conserv. 40:157–161.

Lemunyon, J.L., and T.C. Daniel. 2002. Quantifying phosphorus losses from the agricultural system. J. Soil Water Conserv. 57:399–401.

Mallarino, A.P., B.M. Stewart, J.L. Baker, J.A. Downing, and J.E. Sawyer. 2005. Background and basic concepts of the Iowa phosphorus index. Available at ftp://ftp-fc.sc.egov.usda.gov/IA/technical/BackgroundBasics.pdf (verified 1 May 2009). Iowa State University, Ames.

McDowell, R.W., and W. Catto. 2005. Alternative fertilizers and management to decrease incidental phosphorus loss. Environ. Chem. Lett. 2:169–174.

McDowell, L.L., and K.C. McGregor. 1980. Nitrogen and phosphorus losses in runoff from no-till soybeans. Trans. ASAE 23:643–648.

McDowell, R.W., R.M. Monaghan, and P.L. Carey. 2003. Potential phosphorus losses in overland flow from pastoral soils receiving long-term applications of either superphosphate or reactive phosphate rock. N. Z. J. Agric. Res. 46:329–337.

McGrath, J.M., J.T. Sims, R.O. Maguire, W.W. Saylor, R. Angel, and B.L. Turner. 2005. Broiler diet modification and litter storage: Impacts on phosphorus in litters, soils, and runoff. J. Environ. Qual. 34:1896–1909.

Menzel, R.G. 1980. Enrichment ratios for water quality modeling. p. 486–492. *In* CREAMS A field scale model for chemicals, runoff, and erosion from agricultural management systems. Vol. 3. USDA-SEA-Conserv. Res. Report. USDA-SEA, Washington, DC.

Minnesota P Index Technical Guide. 2006. Available at http://www.mnpi.umn.edu/downloadfiles/MNPIndexTechGuide200608.pdf (verified 1 May 2009). Univ. of Minnesota, St. Paul.

Moore, P.A., Jr., and D.R. Edwards. 2007. Long-term effects of poultry litter, alum-treated litter, and ammonium nitrate on phosphorus availability in soil. J. Environ. Qual. 36:163–174.

Mueller, D.H., R.C. Wendt, and T.C. Daniel. 1984. Phosphorus losses as affected by tillage and manure application. Soil Sci. Soc. Am. J. 48:901–905.

Nash, J.E., and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models. Part 1. A discussion of principles. J. Hydrol. 10:282–290.

National Resource Conservation Service. 2004. Estimation of direct runoff from storm rainfall. *In* Part 630 Hydrology, National engineering handbook. Available at http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17752.wba (verified 4 May 2009). USDA-NRCS, Wahington, DC.

Nicholaichuk, W., and D.W.L. Read. 1978. Nutrient runoff from fertilized and unfertilized fields in western Canada. J. Environ. Qual. 7:542–544.

Owens, L.B., and M.J. Shipitalo. 2006. Surface and subsurface phosphorus losses from fertilized pasture systems in Ohio. J. Environ. Qual. 35:1101–1109.

Panuska, J.C., K.G. Karthikeyan, and J.M. Norman. 2008. Sediment and phosphorus losses in snowmelt and rainfall runoff from three corn management systems. Trans. ASABE 51:95–105.

Pierson, S.T., M.L. Cabrera, G.K. Evanylou, H.H. Kuykendall, C.S. Hoveland, M.A. McCann, and L.T. West. 2001. Phosphorus and ammonium concentrations in surface runoff from grasslands fertilized with broiler litter. J. Environ. Qual. 30:1784–1789.

Reese, L.E., R.O. Hegg, and R.E. Gantt. 1982. Runoff water quality from dairy pastures in the piedmont region. Trans. ASAE 25:697–701.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. Predicting soil erosion by water: A guide to conservation planning with the revised Universal Soil Loss Equation (RUSLE). U.S. Dep. Agric. Handb. 703. USDA, Washington, DC.

SAS Institute. 1999. Version 8. SAS Inst., Cary, NC.

Schroeder, P.D., D.E. Radcliffe, and M.L. Cabrera. 2004. Rainfall timing and poultry litter application rate effects on phosphorus loss in surface runoff. J. Environ. Qual. 33:2201–2209.

Seo, Y., J. Lee, W.E. Hart, H.P. Denton, D.C. Yoder, M.E. Essington, and E. Perfect. 2005. Sediment loss and nutrient runoff from three fertilizer application methods. Trans. ASAE 48:2155–2162.

Shah, S.B., J.L. Miller, and T.J. Basden. 2004. Mechanical aeration and liquid dairy manure application impacts on grassland runoff water quality and yield. Trans. ASAE 47:777–788.

Sharpley, A.N. 1980. The enrichment of soil phosphorous in runoff sediments. J. Environ. Qual. 9:521–526.

Sharpley, A.N., C.A. Jones, C. Gray, and C.V. Cole. 1984. A simplified soil and plant phosphorus model: II. Prediction of labile, organic, and sorbed phosphorus. Soil Sci. Soc. Am. J. 48:805–809.

Sharpley, A.N., P.J.A. Kleinman, R.W. McDowell, M. Gitau, and R.B. Bryant. 2002. Modeling phosphorus transport in agricultural watersheds: Processes and possibilities. J. Soil Water Conserv. 57:425–439.

Sharpley, A.N., and S. Rekolainen. 1997. Phosphorus in agriculture and its environmental implications. p. 1–54. *In* H. Tunney et al. (ed.) Phosphorus loss from soil to water. CAB International Press, Cambridge, England.

Sharpley, A.N., U. Singh, G. Uehara, and J. Kimble. 1989. Modeling soil and plant phosphorus dynamics in calcareous and highly weathered soils. Soil Sci. Soc. Am. J. 53:153–158.

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. J. Soil Water Conserv. 58:137–152.

Shigaki, F., A.N. Sharpley, and L.I. Prochnow. 2006. Source-related transport of phosphorus in surface runoff. J. Environ. Qual. 35:2229–2235.

Shigaki, F., A.N. Sharpley, and L.I. Prochnow. 2007. Rainfall intensity and phosphorus source effects on phosphorus transport in surface runoff from soil trays. Sci. Total Environ. 373:334–343.

Sigua, G.C., M.J. Williams, S.W. Coleman, and R. Starks. 2006. Nitrogen and phosphorus status of soils and trophic state of lakes associated with forage-based beef cattle operations in Florida. J. Environ. Qual. 35:240–252.

Sistani, K.R., G.E. Brink, and J.L. Oldham. 2008. Managing broiler litter application rate and grazing to decrease watershed runoff losses. J. Environ. Qual. 37:718–724.

Smith, K.A., D.R. Jackson, and P.J.A. Withers. 2001. Nutrient losses by surface run-off following application of organic manures to arable land. II. Phosphorus. Environ. Pollut. 112:53–60.

Smith, L.C., and R.M. Monaghan. 2003. Nitrogen and phosphorus losses in overland flow from a cattle-grazed pasture in Southland. N. Z. J. Agric. Res. 46:225–237.

Soileau, J.M., J.T. Touchton, B.F. Hajek, and K.H. Yoo. 1994. Sediment, nitrogen, and phosphorus runoff with conventional and conservation tillage cotton in a small watershed. J. Soil Water Conserv. 49:82–89.

Stott, D.E., E.E. Alberts, and M.A. Weltz. 1995. Residue decomposition and management component. p. 9.1–9.16. *In* D.C. Flanagan and M.A. Nearing (ed.) USDA-Water Erosion Prediction Project (WEPP) Hillslope Profile and Watershed Model Documentation. Rep. 10. USDA-ARS, NSERL, West Lafayette, IN.

Thoma, D.P., S.C. Gupta, J.S. Strock, and J.F. Moncrief. 2005. Tillage and nutrient source effects on water quality and corn grain yield from a flat landscape. J. Environ. Qual. 34:1102–1111.

Vadas, P.A. 2006. Distribution of phosphorus in manure slurry and its infiltration after application to soils. J. Environ. Qual. 35:542–547.

Vadas, P.A., B.E. Haggard, and W.J. Gburek. 2005a. Predicting phosphorus in runoff from manured field plots. J. Environ. Qual. 34:1347–1353.

Vadas, P.A., P.J.A. Kleinman, and A.N. Sharpley. 2004. A simple method to predict dissolved phosphorus in runoff from surface-applied manures. J. Environ. Qual. 33:749–756.

Vadas, P.A., P.J.A. Kleinman, and A.N. Sharpley. 2005b. Relating soil phosphorus to dissolved phosphorus in runoff: A single extraction coefficient for water quality modeling. J. Environ. Qual. 34:572–580.

Vadas, P.A., T. Krogstad, and A.N. Sharpley. 2006. Modeling phosphorus transfer between labile and non-labile soil pools: Updating the EPIC model. Soil Sci. Soc. Am. J. 70:736–743.

Vadas, P.A., W.J. Gburek, A.N. Sharpley, P.J.A. Kleinman, P.A. Moore, Jr., M.L. Cabrera, and R.D. Harmel. 2007a. A model for phosphorus transformation and runoff loss for surface-applied manures. J. Environ. Qual. 36:324–332.

Vadas, P.A., R.D. Harmel, and P.J.A. Kleinman. 2007b. Transformations of soil and manure phosphorus after surface application of manure to field plots. Nutr. Cycling Agroecosyst. 77:83–99.

Vadas, P.A., L.B. Owens, and A.N. Sharpley. 2008. An empirical model for dissolved phosphorus in runoff from surface-applied fertilizers. Agric. Ecosyst. Environ. 127:59–65.

Vervoort, R.W., D.E. Radcliffe, M.L. Cabrera, and M. Latimore, Jr. 1998. Nutrient losses in surface and subsurface flow from pasture applied poultry litter and composted poultry litter. Nutr. Cycling Agroecosyst. 50:287–290.

Vories, E.D., T.A. Costello, and R.E. Glover. 2001. Runoff from cotton fields fertilized with poultry litter. Trans. ASAE 44:1495–1502.

Warren, J.G., C.J. Penn, J.M. McGrath, and K. Sistani. 2008. The impact of alum addition on organic P transformations in poultry litter and litter-amended soil. J. Environ. Qual. 37:469–476.

Westerman, P.W., L.D. King, J.C. Burns, G.A. Cummings, and M.R. Overcash. 1987. Swine manure and lagoon effluent applied to a temperate forage mixture: II. Rainfall runoff and soil chemical properties. J. Environ. Qual. 16:106–112.

Westerman, P.W., M.R. Overcash, R.O. Evans, L.D. King, J.C. Burns, and G.A. Cummings. 1985. Swine lagoon effluent applied to coastal bermudagrass: III. Irrigation and rainfall runoff. J. Environ. Qual. 14:22–25.

Wisconsin Buffer Initiative. 2005. A report to the Wisconsin Natural Resources Board. Available at http://bombadil.lic.wisc.edu/WBI/reports.htm (verified 1 May 2009). UW-Madison, Madison, WI.

Withers, P.J.A., and G.A. Bailey. 2003. Sediment and phosphorus transfer in overland flow from a maize field receiving manure. Soil Use Manage. 19:28–35.

Withers, P.J.A., S.D. Clay, and V.G. Breeze. 2001. Phosphorus transfer in runoff following application of fertilizer, manure, and sewage sludge. J. Environ. Qual. 30:180–188.

Wood, B.H., C.W. Wood, K.H. Yoo, K.S. Yoon, and D.P. Delaney. 1999. Seasonal surface runoff losses of nutrients and metals from soils fertilized with boiler litter and commercial fertilizer. J. Environ. Qual. 28:1210–1218.

Wortmann, C.S., and D.T. Walters. 2006. Phosphorus runoff during four years following composted manure application. J. Environ. Qual. 35:651–657.

Young, R.A., and R.F. Holt. 1977. Winter-applied manure: Effects on annual runoff, erosion, and nutrient movement. J. Soil Water Conserv. 32:219–222.

Young, R.A., and C.K. Mutchler. 1976. Pollution potential of manure spread on frozen ground. J. Environ. Qual. 5:175–179.