

A Model for Phosphorus Transformation and Runoff Loss for Surface-Applied Manures

P. A. Vadas,* W. J. Gburek, A. N. Sharpley, P. J. A. Kleinman, P. A. Moore, Jr., M. L. Cabrera, and R. D. Harmel

ABSTRACT

Agricultural P transport in runoff is an environmental concern. An important source of P runoff is surface-applied, unincorporated manures, but computer models used to assess P transport do not adequately simulate P release and transport from surface manures. We developed a model to address this limitation. The model operates on a daily basis and simulates manure application to the soil surface, letting 60% of manure P infiltrate into soil if manure slurry with less than 15% solids is applied. The model divides manure P into four pools, water-extractable inorganic and organic P, and stable inorganic and organic P. The model simulates manure dry matter decomposition, and manure stable P transformation to water-extractable P. Manure dry matter and P are assimilated into soil to simulate bioturbation. Water-extractable P is leached from manure when it rains, and a portion of leached P can be transferred to surface runoff. Eighty percent of manure P leached into soil by rain remains in the top 2 cm, while 20% leaches deeper. This 2-cm soil layer contributes P to runoff via desorption. We used data from field studies in Texas, Pennsylvania, Georgia, and Arkansas to build and validate the model. Validation results show the model accurately predicted cumulative P loads in runoff, reflecting successful simulation of the dynamics of manure dry matter, manure and soil P pools, and storm-event runoff P concentrations. Predicted runoff P concentrations were significantly related to ($r^2 = 0.57$) but slightly less than measured concentrations. Our model thus represents an important modification for field or watershed scale models that assess P loss from manured soils.

NONPOINT-SOURCE pollution of fresh waters by agricultural P can accelerate eutrophication and limit water use for drinking, recreation, and industry (Sharpley and Rekolainen, 1997; Carpenter et al., 1998; Gibson et al., 2000). A major pathway of P transport from agricultural soils is surface runoff, to which mismanaged or excessive surface application of unincorporated animal manures can be important contributors (Kleinman and Sharpley, 2003; DeLaune et al., 2004a, 2004b). Recent research has concentrated on better understanding and minimizing P transport in runoff from surface-applied, unincorporated manures (Harmel et al., 2004; Moore et al., 2000). Computer simulation models that quantify field or watershed-scale P transport, such as EPIC (Williams et al., 1983), GLEAMS (Leonard et al., 1987),

ANSWERS (Bouraoui and Dillaha, 1996), or SWAT (Arnold et al., 1998), are also used to improve management to minimize offsite P transport (Sharpley et al., 2002). The models generally use similar P routines, which adequately simulate manure applications for tilled systems where manure is well mixed into soil. However, the models do not adequately simulate surface application of manures or direct transfer of P from manures on the soil surface to runoff (Pierson et al., 2001b; Sharpley et al., 2002). If such models are used where surface-applied, unincorporated manures are common, they should be modified to better simulate P in runoff from manures.

Vadas et al. (2004, 2005a) developed a model to predict dissolved P release from surface-applied, unincorporated manures during rain events and its transfer to soil or runoff. Using laboratory and small field-plot data, they showed the model successfully predicted P in runoff from manures for individual rain events. However, incorporating this manure P runoff model into existing models such as EPIC or SWAT necessitates developing routines that also simulate different methods of manure application and physical and chemical weathering of manure in the field through time. The objectives of this paper are to describe the development of such a surface manure and runoff P model and validate the model with independent data.

MATERIALS AND METHODS

Model Description

Model Structure and Initial Parameters

The manure P runoff model is written in FORTRAN and runs on a daily time step. Required soil, climate, and hydrology input data currently include initial soil P content (mg kg^{-1}), daily average temperature ($^{\circ}\text{C}$), rainfall (mm), and runoff (mm). Runoff data could be generated by models such as EPIC or SWAT. The model simulates interconnected pools of manure dry matter and P on the soil surface, flows of manure P between pools, leaching and assimilation of manure P into soil, and loss of manure P to runoff (Fig. 1). All manure P units are in kg.

When manure is surface-applied, required input data include date of application, application area (ha), mass of manure dry matter applied (kg), manure total P (TP), water-extractable inorganic P (WEP_i), and water-extractable organic P (WEP_o) (%). The model assumes manure evenly covers the entire application area. If manure slurry with dry matter content less than ~15% is applied, the model assumes manure solids remaining on the surface cover 50% of the application area, regardless of the exact solids content. This is a physically reasonable assumption that improved predictions during model testing, but we could find no data in the literature on the topic. Future research should investigate this topic, specifically if manure coverage varies based on manure solids content. Manure

P.A. Vadas, USDA-ARS, U.S. Dairy Forage Research Center, 1925 Linden Drive West, Madison, WI 53706. W.J. Gburek, P.J.A. Kleinman, and A.N. Sharpley, USDA-ARS, Pasture Systems and Watershed Management Research Unit, Building 3702, Curtin Road, University Park, PA 16802-3702. P.A. Moore, Jr., USDA-ARS, Poultry Production and Product Safety Research Unit, Plant Sciences 115, Fayetteville, AR 72701. M.L. Cabrera, Dep. Crop and Soil Sciences, Univ. of Georgia, Athens, GA 30602. R.D. Harmel, USDA-ARS, Grassland, Soil, and Water Research Lab., 808 E. Blackland Rd., Temple, TX 76702. Received 31 May 2006. *Corresponding author (vadas@wisc.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: TP, manure total P; WEP_i , manure water-extractable inorganic P; WEP_o , manure water-extractable organic P.

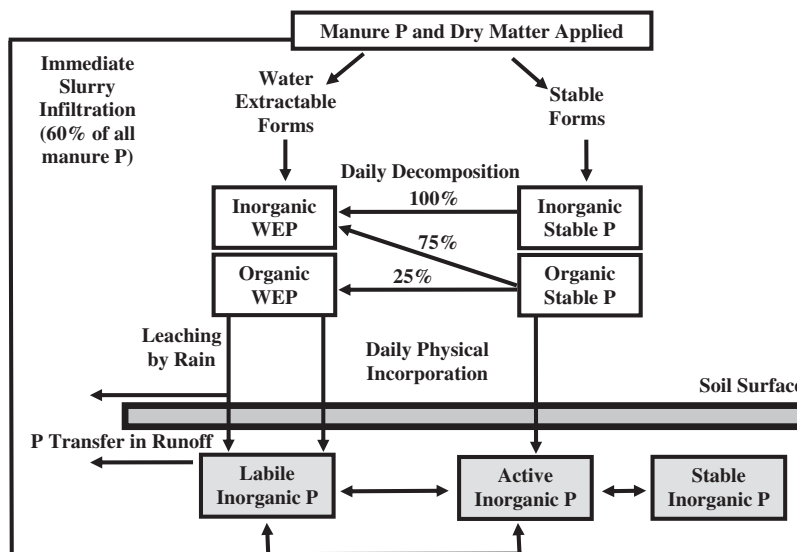
Manure P and Runoff Model – Initial Pools and Interactions

Fig. 1. Schematic depiction of manure and soil P pools, and pathways of P transformation between the pools.

TP is measured by digestion, such as Bremner (1996). Manure WEP_I and WEP_O pools represent P that can be leached from manure by rain. Manure WEP_I is measured by shaking fresh manure with deionized water at a dry weight equivalent, water to manure solids ratio of 250:1 for 1 h, filtering extracts through 0.45- μ m filters, and measuring P in filtrates colorimetrically (Murphy and Riley, 1962). Manure WEP_O is estimated by digesting the same filtrates, analyzing digests for P colorimetrically, and calculating the difference in P between digested and undigested samples. Filtered, undigested extracts could also be analyzed by inductively coupled plasma (ICP) spectroscopy, with the difference between colorimetric and ICP results representing WEP_O. Manure water extraction data are becoming more common (Bundy et al., 2004; Kleinman et al., 2005; Vadas and Kleinman, 2006), but most extractions will not use the procedure required for our model, particularly the 250:1 extraction ratio. However, data from any extraction ratio can be extrapolated to estimate manure P at a 250:1 ratio using regression figures relating extraction ratio to extractable P in Vadas et al. (2005a).

When manure is surface-applied (Fig. 1), the difference between manure TP and the sum of WEP_I and WEP_O is stable P, which is manure P that is not leachable by rain but is transformed to WEP_I or WEP_O as manure decomposes. Manure stable P can constitute from 50 to 70% of manure TP and can thus be a significant source of manure WEP_I or WEP_O as manure ages. The model automatically divides stable P into inorganic (25%) and organic P (75%) for later daily decomposition. The 25/75 default is from sequential fractionation studies that estimated inorganic and organic P forms in manure (Dou et al., 2000; Sharpley and Moyer, 2000; He and Honeycutt, 2001; He et al., 2003a; Turner and Leytem, 2004; Ajiboye et al., 2004; McDowell and Stewart, 2005; McGrath et al., 2005; He et al., 2006b). All studies used a modified Hedley et al. (1982) fractionation, for which we assumed NaOH-extractable, HCl-extractable, and residual P to represent model stable P. When HCl-extractable P was not fractionated into organic and inorganic P, we assumed 65% of this P was inorganic (He et al., 2006a). We also assumed all residual P was organic. The 25/75 stable P division is an area of active research that requires more investigation and may not be ap-

propriate for simulations of manures chemically amended to decrease P solubility (Moore et al., 2000; Peak et al., 2002). Our model could be easily modified to allow manure P fractions to be user-defined, so management options such as manure chemical treatment could be simulated. Finally, if manure slurry with less than ~15% solids is applied, the model assumes slurry liquid immediately infiltrates into soil and adds 60% of all manure P to corresponding soil P pools. Vadas et al. (2004) observed it was necessary to account for such slurry P infiltrations to successfully predict P in runoff from surface manures. Vadas (2006) observed that at manure solids content greater than ~15%, there was not a freely draining liquid portion of manure that could immediately infiltrate on application to soil. Vadas (2006) had data from only one soil type and two manure slurry types and recognized the possibility that the degree of slurry P infiltration could vary from our assumed 60% based on soil type or manure solids content. Future research should investigate this topic.

Manure Dry Matter and Phosphorus Decomposition

Using modified routines from GLEAMS (Leonard et al., 1987), the model simulates manure dry matter decomposition (Fig. 1) as a function of mean daily air temperature and manure moisture and age factors as:

$$AWDCR = AWRC \times TFA \times WFA \quad [1]$$

where AWDCR is a unitless decomposition factor and is multiplied by current dry matter to calculate daily decomposition. The unitless temperature factor TFA, taken directly from GLEAMS, varies between 0.0 and 1.0 and is calculated as:

$$TFA = T/[T + \text{EXP}(9.93 - 0.312 \times T)] \quad [2]$$

where T is average daily air temperature in degrees Celsius. The unitless manure age factor AWRC, modified from GLEAMS to improve simulations during model development, varies between 0.01 and 0.4 and is calculated as:

$$\text{IF (Current manure dry matter/Manure dry matter applied)} \geq 0.9 \text{ AWRC} = 0.4 \quad [3]$$

$$\text{IF } 0.9 > (\text{Current manure dry matter/Manure dry matter applied}) \geq 0.6 \text{ AWRC} = 0.1 \quad [4]$$

$$\text{IF } (\text{Current manure dry matter/Manure dry matter applied}) < 0.6 \text{ AWRC} = 0.01 \quad [5]$$

The WFA, modified from Schomberg et al. (1996) to improve simulations during model development, varies between 0.01 and 0.5 and is calculated as:

$$\text{WFA} = (\text{MOIST} - 0.05)/(0.5 - 0.05) \times 0.5 \quad [6]$$

If daily rain is more than 4 mm, manure moisture content (MOIST) is set to 0.5 to represent optimum conditions. The WFA has a minimum of 0.01 to represent dry conditions of minimal decomposition. Without rain, MOIST decreases daily in proportion to temperature as:

$$\text{MOIST} = \text{MOIST} - (0.1 \times \text{TFA}) \quad [7]$$

As manure dry matter decreases due to decomposition, measured as percentage of manure dry matter initially applied in Eq. [3] through [5], its decomposition rate slows, reflecting the increasing proportion of remaining recalcitrant dry matter. When manure is applied before a previous application entirely decomposes, the model combines new and existing dry matter to represent 'manure dry matter applied' in Eq. [3]. The area that manure covers decreases at the same rate as dry matter decomposition. Appropriately simulating decomposition of dry matter and cover ensures appropriate rain interaction with manure, which in turn predicts P leaching from manure during a storm. If our manure P runoff model is incorporated into existing models, these manure dry matter decomposition equations could be replaced by existing residue decomposition equations.

Based on field and lab data of Vadas et al. (2006a) and McGrath et al. (2005), our model transforms manure stable P to WEP_i and WEP_o (Fig. 1) as manure ages, but independent from any soil P processes. We determined manure P decomposition pathways and rates from data of McGrath et al. (2005), who show that manure stable P decomposes as a function of temperature and moisture, with organic P decreasing more than inorganic P. In the model, stable organic P (MANSOP) decomposes as:

$$\text{MSOPDCOM} = \text{MANSOP} \times 0.01 \times (\text{TFA} \times \text{WFA}) \quad [8]$$

where MSOPDCOM is the amount of stable organic P decomposed each day (kg). Decomposed organic P is added to WEP_i (75%) and WEP_o (25%) (Fig. 1). Decomposition is a function of a daily 0.01 rate, which we calculated from data of McGrath et al. (2005).

Manure stable inorganic P decomposes (Fig. 1) according to Eq. [8], but with a rate factor of only 0.0025 because data of McGrath et al. (2005) showed only small decreases in stable inorganic P through time. All decomposed stable inorganic P is added to manure WEP_i . Because data from McGrath et al. (2005) also indicated decomposition of WEP_o as manure ages, modeled manure WEP_o decomposes (Fig. 1) according to Eq. [6], but with a rate factor of 0.1. The 0.1 rate was calculated from data of McGrath et al. (2005) so that WEP_o is more readily decomposed than stable organic P. All decomposed WEP_o is added to manure WEP_i . We modeled manure dry matter and P decomposition to agree with 14- to 18-mo-long field observations of Vadas et al. (2006a) and to ensure there is no unrealistic, long-term buildup of manure or P on the soil surface. Data concerning long-term manure and P transformations in the field are limited (Tasistro et al., 2004; Vadas

et al., 2006a). We know that manure P transforms to water-extractable forms over time, but there are few data available to elucidate controlling mechanisms or the best way to model these mechanisms (He et al., 2003b). Additional investigation of the controlling mechanisms would provide needed information for manure and P modeling.

To avoid buildup of manure or P on the soil surface, our model also simulates slow, physical assimilation of manure dry matter and P into soil to represent incorporation by macro-invertebrates (bioturbation) or rain (Fig. 1). Slow assimilation is calculated the same way for manure dry matter and all manure P pools. Equation [9] shows an example calculation for WEP_i (MANWIP) assimilation as:

$$\text{MWIPDCOM} = 30.0 \times (\text{MANWIP/MANMASS}) \times \text{MANCOV} \times \text{TFA} \quad [9]$$

where MANMASS is current manure dry matter mass (kg), MWIPDCOM is daily WEP_i assimilated (kg), 30.0 is daily manure dry matter assimilation (kg ha^{-1}), and MANCOV is the current area covered by manure (ha). Gallagher and Wollenhaupt (1997) observed an assimilation rate for alfalfa residue of $23 \text{ kg ha}^{-1} \text{ d}^{-1}$ from March to May in Wisconsin. Esse et al. (2001) observed a greater rate of manure assimilation of $30 \text{ kg ha}^{-1} \text{ d}^{-1}$ from June to October in West Africa. Given the high temperatures and insect activity in the Africa study, we set this $30 \text{ kg ha}^{-1} \text{ d}^{-1}$ rate as an upper limit. Assimilation of manure P, as in Eq. [9], is tempered by daily air temperature and is determined by multiplying the 30.0 rate by the current ratio of manure P to manure dry matter (MANWIP/MANMASS for WEP_i). The MANCOV is included to calculate incorporation in kg.

Phosphorus Leaching from Manure by Rain

When rain falls, WEP_i and WEP_o are leached from manure (Fig. 1) based on the rain to manure dry matter ratio (W , $\text{cm}^3 \text{ g}^{-1}$) (Vadas et al., 2004, 2005a). An example calculation for WEP_i is:

$$\text{Dairy: } \text{WEP}_i \text{ Leached} = [1.2 (W/(W + 73.1))] \times (\text{Manure } \text{WEP}_i) \quad [10]$$

$$\text{Poultry and Swine: } \text{WEP}_i \text{ Leached} = [2.2 (W/(W + 300.1))] (\text{Manure } \text{WEP}_i) \quad [11]$$

Leaching of WEP_o is calculated with Eq. [10] or [11] but is multiplied by a factor of 1.6 (Vadas et al., 2004, 2005a). The W is calculated as:

$$W = (\text{RAIN})/(\text{MANMASS})(\text{MANCOV})(100\,000) \quad [12]$$

where RAIN is in cm, and 100 000 ensures $\text{cm}^3 \text{ g}^{-1}$ units. If runoff occurs, some leached manure P is transferred to runoff, with the concentration of dissolved P in runoff (mg L^{-1}) calculated as:

$$\text{Runoff Dissolved P} = \text{Manure } \text{WEP} \text{ Leached}/\text{RAIN}/(\text{AREA})(10)(\text{PDFACTOR}) \quad [13]$$

Equation [13] calculates a concentration of WEP leached from manure and then multiplies it by a PDFACTOR, which is a P distribution factor that varies between 0.0 and 1.0, to calculate the runoff P concentration (Vadas et al., 2005a). The PDFACTOR is calculated as:

$$\text{PDFACTOR} = (\text{RUNOFF}/\text{RAIN})^{0.225} \quad [14]$$

We modified Eq. [14] from Vadas et al. (2005a) to improve predictions during model calibration. The AREA is used in Eq. [13] (instead of MANCOV as in Eq. [12]) so that runoff generated from areas not covered by manure will dilute P concentrations in runoff from areas covered by manure. A mass of P in runoff (kg or kg ha⁻¹) is calculated by multiplying runoff P concentrations by runoff volumes. Manure P that infiltrates into soil is calculated as the difference between P leached from manure and P transported in runoff. For infiltrated manure P, 80% is added to soil pools in the top 2 cm of soil (Vadas et al., 2006a), with 20% infiltrating deeper.

To calculate a dissolved P concentration in runoff from manure, it is critical to first calculate a concentration of P leached from manure and then multiply that concentration by PDFACTOR to calculate a P concentration in runoff. Runoff P loads are then calculated by multiplying predicted runoff P concentrations with runoff volumes. Predictions of P in runoff will be incorrect if the mass of P leached out of manure is simply multiplied by PDFACTOR to determine mass of P loss in runoff. This is true because P leaching from manure during a storm is dynamic, with more P leached from manure early in a storm before runoff typically occurs (Vadas et al., 2004, 2005b). Currently, our model does not simulate P leaching or runoff loss from frozen manures, as would occur in colder climates. Future research should investigate how P leaching and subsequent loss in runoff differ for frozen manure or snow-melt conditions.

Soil Phosphorus

For simplicity, our model simulates only those soil P dynamics that are most important for dissolved P loss from soil to runoff. It does not consider organic P transformations, plant growth or P uptake, or erosion. However, our model is designed to be incorporated into more complex models that simulate these latter processes (Sedorovich et al., 2006). The lack of soil organic P simulation does not affect manure stable organic P transformations described earlier, as the two are intended to operate independently. Our soil P model is based on EPIC and simulates three inorganic P pools in a 2 cm surface soil layer (Fig. 1). Labile inorganic P represents easily desorbable P available to runoff and is measured by extraction with Fe-oxide strips (Chardon, 2000; Vadas et al., 2006b). Labile Inorganic P can be estimated with other methods that quantify a similar amount of easily desorbable P (Vadas et al., 2006b), as long as those methods are consistently used, as described later in validation studies. Users input initial labile inorganic P in mg kg⁻¹, which the model converts to kg. Active inorganic P is not easily desorbable, is in equilibrium with labile inorganic P, and is initialized as:

$$\text{Active Inorganic P} = (\text{Labile Inorganic P}) \times (1 - \text{PSC})/\text{PSC} \quad [15]$$

where PSC is a unitless P sorption coefficient that represents how much inorganic P added to soil remains labile inorganic P on reaching relative equilibrium. The PSC is estimated from soil properties (Sharpley et al., 1984, 1989). Soil stable inorganic P is in equilibrium with active inorganic P and is initialized as:

$$\text{Stable Inorganic P} = \text{Active Inorganic P} \times 4.0 \quad [16]$$

Movement of P between the three soil P pools (Eq. [15] and [16]) is based on EPIC with modifications of Vadas et al. (2006b).

When manure slurry is applied to soil, slurry WEP_i that immediately infiltrates is added to soil labile inorganic P (Fig. 1). This added manure P can then be gradually transformed to soil active inorganic P, which is not available to dissolved loss

in runoff. Manure slurry inorganic stable P that immediately infiltrates is added to soil active inorganic P. When rain leaches manure WEP_i into soil, 80% is added to soil labile P (Fig. 1), with 20% infiltrating deeper than 2 cm (Vadas et al., 2006b). For slow, physical assimilation, manure WEP_i is added to soil labile inorganic P, and manure inorganic stable P is added to soil active inorganic P. Concentrations of dissolved inorganic P in runoff from soil labile inorganic P are determined as:

$$\text{Runoff Dissolved P} = \text{Labile Inorganic P} \times 0.004 \quad [17]$$

where runoff dissolved P is in mg L⁻¹ and soil labile inorganic P is in mg kg⁻¹. This relationship is from Vadas et al. (2005b) and assumes labile inorganic P is half of Mehlich-3 soil P (Mehlich, 1984; Vadas et al., 2006a). A mass load of runoff P (kg or kg ha⁻¹) from soil is calculated by multiplying runoff P concentrations by runoff volumes.

Model Testing and Validation

To build and calibrate our model, we used field data from the study of Vadas et al. (2006a), which was designed to measure simulated manure and soil P pools and runoff P through time after a surface application of manure. In that study, dairy and poultry manure were applied on porous, fabric sheets on small plots in Pennsylvania and Texas. The fabric allowed rain to leach through manure, while separating manure and underlying soil for discrete sampling. Manure was covered with a second porous fabric to prevent wash-off. Manure and underlying soil were sampled periodically for 14 to 18 mo. Soils from 0 to 2 cm were analyzed for Fe oxide strip P to represent labile P in the model (Vadas et al., 2006b), and manures were analyzed for TP, WEP_i, and WEP_o to represent model manure P pools. In Pennsylvania, poultry and dairy manure were also applied to 0.7- by 1.3-m runoff plots, but without sheets. Naturally occurring runoff was collected, measured, and analyzed for dissolved inorganic P. Climate data were collected at field sites.

To validate our model, we used independent field data sets from Georgia (Pierson et al., 2001a; Tasistro et al., 2004) and Arkansas (Edwards et al., 1996). Because the runoff studies of Pierson et al. (2001a) and Edwards et al. (1996) were conducted on pastures that had very little erosion, our model was appropriate for simulating these systems. In the Tasistro et al. (2004) study, stainless steel cylinders were inserted in a bermudagrass pasture in February. Cylinders extended 1 cm above the soil surface to retain thatch and prevent runoff. Fresh poultry litter was analyzed for TP, WEP_i, and WEP_o by the same methods used for manure P pools in our model, and was applied at a rate of 5.0 Mg ha⁻¹. At several times up to 120 d after application, the thatch layer and top 1 cm of soil was removed and analyzed for water-extractable inorganic and organic P. The soil water extraction was a suitable representation of labile inorganic P in our model, as justified by Vadas et al. (2006b). Data from Tasistro et al. (2004) showed that thatch itself contributed little P during water extractions so that data represented P removed from applied poultry litter. We obtained daily climate data from the field site, simulated the experiment of Tasistro et al. (2004), and compared measured and simulated results for manure WEP_i and WEP_o, and soil labile P to validate manure and soil P dynamics in our model.

Edwards et al. (1996) conducted a study on four tall fescue pastures in Arkansas from September 1991 through April 1994. Fields were designated as RM (1.23 ha), RA (0.57 ha), WM (1.06 ha), and WA (1.46 ha), with R and W indicating the

site location, M indicating fields that received poultry manure, and A indicating fields that received only ammonium nitrate fertilizer. Field RM received two applications of poultry slurry with 12% dry matter, and field WM received five applications of poultry litter (average of 25% moisture content). Because manure was not analyzed for water-extractable P, we assumed manure WEP_I was 29% and WEP_O was 4% of TP (Sharpley and Moyer, 2000; Kleinman et al., 2002; Haggard et al., 2005; Kleinman et al., 2005; Vadas and Kleinman, 2006). For poultry slurry, we assumed manure WEP_I was 44% and WEP_O was 4% of TP. All fields were grazed by dairy cattle periodically, with monthly grazing schedules reported in animal units ha^{-1} . We assumed one animal unit represented 450 kg (USDA-ERS, 2006) and produced 5.4 kg dry weight of feces each day (ASAE, 2003) that covered an area of 1.42 m^2 (James, 2005). We assumed cattle manure contained 0.78% TP (ASAE, 2003), of which 50% was WEP_I and 5% was WEP_O (Chapuis-Lardy et al., 2004; Kleinman et al., 2005; McDowell and Stewart, 2005). Edwards et al. (1996) reported initial Mehlich-3 soil P data from a depth of 0 to 15 cm. We assumed soil labile P was half of Mehlich-3 P (Vadas et al., 2006a), but that soil P in the modeled 0- to 2-cm soil layer was double that measured in the 0- to 15-cm layer due to soil P stratification (Daniels et al., 2006; Vadas et al., 2006c). Soil Mehlich-3 P was similarly measured periodically throughout the study. We compared simulated labile P to measured soil P by always making the same corrections. We did not simulate growth of pasture grass, but did remove 25 $kg\ ha^{-1}$ of P from soil labile P incrementally over 180 d between April and October to simulate grass P uptake (Coblentz et al., 2006). Fields were hydrologically isolated and runoff was collected and analyzed for dissolved inorganic and total P. We input measured rainfall and runoff data and compared measured and simulated results for dissolved inorganic P concentrations and loads in runoff, total P loads in runoff, and soil labile P concentrations.

Pierson et al. (2001a) conducted a field study from January 1995 through March 1998 on six fescue-common bermudagrass, 0.75 ha, hydrologically isolated paddocks that each drained to a 0.45-m H-flume to measure runoff volume. Runoff was analyzed for dissolved inorganic P, and rain data were recorded at the site. Paddocks were grazed by beef steers fairly continuously from January 1995 through March 1997. We assumed each animal weighed 340 kg, producing 2.9 kg dry wt. of feces each day (ASAE, 2003) that covered an area of 0.76 m^2 (James, 2005). We assumed cattle manure contained 1.1% TP (ASAE, 2003), of which 50% was WEP_I and 5% was WEP_O . Poultry litter was applied in March and October 1995 and March and September 1996. Litter was analyzed for TP and WEP_I . Because the WEP_I extraction was conducted for only 30 min at a water/solids ratio of 200:1, we assumed this extracted 30% less P than a 250:1 extraction for 1 h (Kleinman et al., 2002; Vadas and Kleinman, 2006). Pierson et al. (2001a) reported initial Mehlich-1 soil P data from a depth of 0 to 15 cm. We assumed soil labile P equaled Mehlich-1 P (Gartley et al., 2001; Vadas et al., 2006a; Vadas, unpublished data, 2002), but that soil P in the modeled 0- to 2-cm soil layer was 2.35 times that measured from the 0- to 15-cm layer based on soil P samples from the same study at the same sampling time (Kuykendall et al., 1999). Soil Mehlich-1 P was similarly measured periodically throughout the study. We compared simulated Labile P to measured soil P by always making the same corrections. As described above, we assumed a pasture grass P uptake of 25 $kg\ ha^{-1}$ over 180 d between April and October, used measured rainfall and runoff data as input, and compared measured and simulated results for dissolved inorganic P concentrations and loads in runoff, and soil labile P concentrations.

RESULTS AND DISCUSSION

Figures 2 and 3 show measured and simulated results for data from the field study of Vadas et al. (2006a) that we used to develop and calibrate our model. Figures show the model accurately ($p = 0.05$) simulated cumulative changes in soil labile P in the top 2 cm (Fig. 2a), manure dry matter mass (Fig. 2b), manure total P (Fig. 3a), and manure WEP_I (Fig. 3b). An analysis using the PROC REG function in SAS (SAS Institute, 1999) showed the slopes and intercepts of the regression lines relating predicted and measured values were significantly different from one and zero for dissolved inorganic P (Fig. 2c) and manure WEP_O (Fig. 3c). Vadas et al. (2006a) detail the critical soil and manure temporal dynamics that the model was developed to simulate. We did not calibrate the model differently for the Texas or Pennsylvania sites, or for the dairy or poultry manure plots at the Pennsylvania site. Thus, the model adequately accounts for variations in climate and manure type.

For the Georgia field study of Tasistro et al. (2004), Fig. 4 shows the model successfully simulated changes in soil labile P and manure WEP_I and WEP_O pools. These changes were similar to those for the field study of Vadas et al. (2006a) and represented early, substantial decreases in manure WEP_I (Fig. 4b) and WEP_O (Fig. 4c), with subsequent increases in underlying soil labile P (Fig. 4a), followed by relatively stable concentrations of

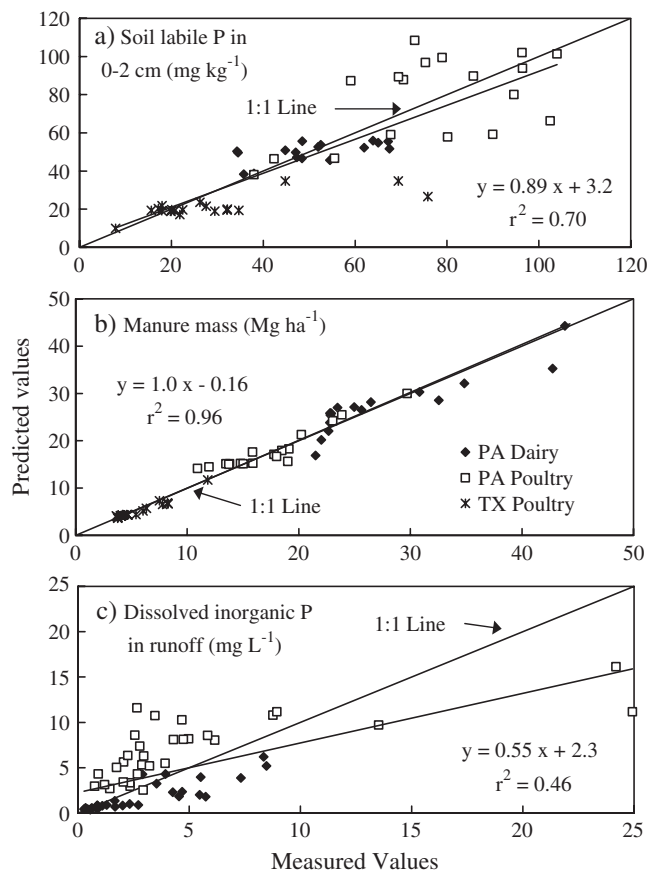


Fig. 2. Measured and simulated results for (a) soil labile P, (b) manure dry matter, and (c) dissolved inorganic P in runoff data from the Pennsylvania and Texas field sites of Vadas et al. (2006a).

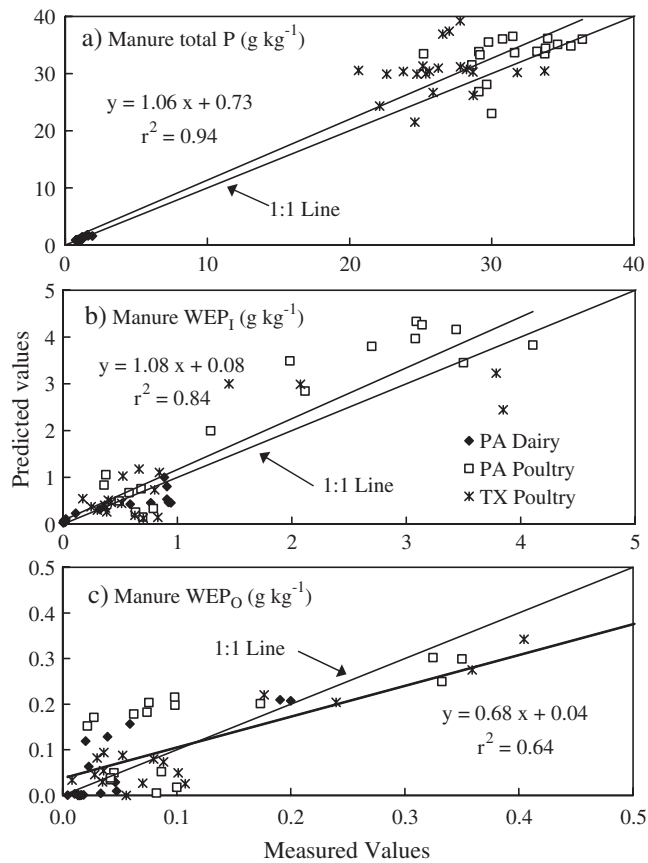


Fig. 3. Measured and simulated results for (a) manure total P, (b) manure WEP₁, and (c) manure WEP₀ data from the Pennsylvania and Texas field sites of Vadas et al. (2006a).

manure and soil P. For the multi-year, field-scale studies of Edwards et al. (1996) in Arkansas and Pierson et al. (2001a) in Georgia, Fig. 5a and 6 show the model accurately ($p = 0.05$) simulated cumulative P loads in runoff (kg ha^{-1}) and changes in soil labile P over the duration of the studies. An analysis using the PROC REG function in SAS (SAS Institute, 1999) showed the slopes and intercepts of the regression lines relating predicted and measured values were not significantly different from unity or zero. For the same Arkansas and Georgia data, Fig. 5b shows simulated dissolved inorganic P concentrations in runoff on a storm-event basis were significantly related ($p = 0.05$) to measured values. However, the slope and intercept of the regression line relating predicted and measured values were significantly ($p = 0.05$) different from unity and zero. Despite the scatter in storm event runoff P prediction data, results indicate the model can reasonably predict the relatively great concentrations (20 mg L^{-1}) that can occur in runoff soon after manure application. Overall, validation results in Fig. 5 and 6 demonstrate the model is flexible enough to simulate widely different management conditions, including machine application of both poultry manure slurry and solids, deposition and transformations of manure from grazing cattle, and a variety of field sizes from 0.57 to 1.46 ha.

Validation data show the model accurately simulated manure and soil P dynamics in long-term scenarios, but

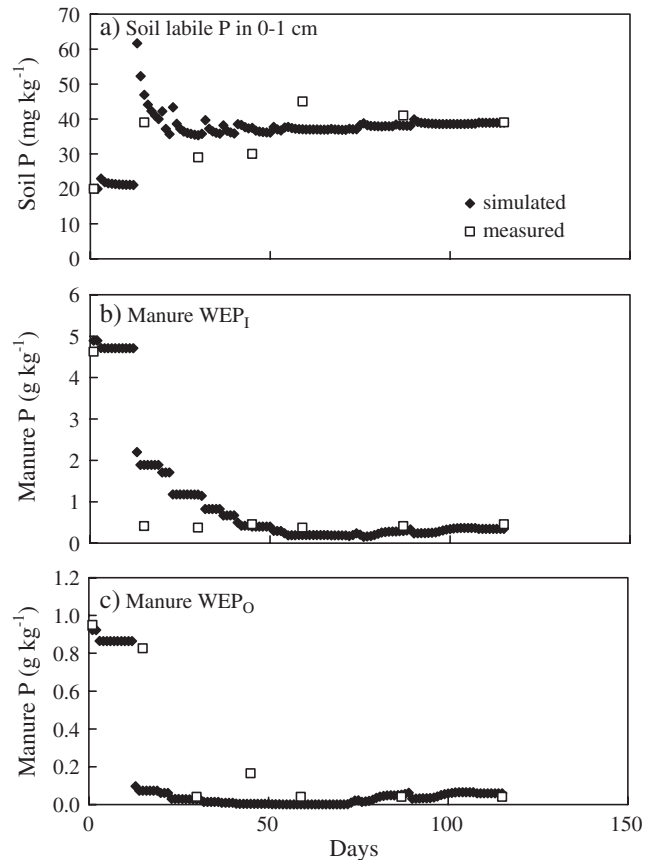


Fig. 4. Measured and simulated results for (a) soil labile P, (b) poultry manure WEP₁, and (c) poultry manure WEP₀ data from a Georgia field site of Tasistro et al. (2004).

somewhat less accurately for individual storm events. However, despite its simplicity, especially for the soil P routines, the model apparently captures the dominant soil, manure, and hydrology processes that control soluble P runoff loss from these surface manure systems. Relatively successful runoff P predictions in turn give confidence that the model can quantify the effect of alternative management practices on P loss in runoff, such as injection of manure slurry, timing of manure application, or chemical amendment of manure to reduce P solubility. Furthermore, we did not calibrate the model differently for any of the validation tests, which demonstrates the model's flexibility.

One particular value of the model is demonstrated well by simulated data in Table 1 for the Arkansas study of Edwards et al. (1996) and the Georgia study of Pierson et al. (2001a). Data are expressed as g of P in runoff per ha per cm of runoff to better normalize and compare P loss across fields, which had varying sizes and amounts of runoff. The model estimates the dynamic fate of applied manure P, including how much P is leached by rain into soil, how much is physically assimilated into soil, and how much P remains on the soil surface. The model thus quantifies different sources of P to runoff, which traditional runoff monitoring does not allow. For example, data in Table 1 show that soil was an important contributor of P to runoff for all four Arkansas fields,

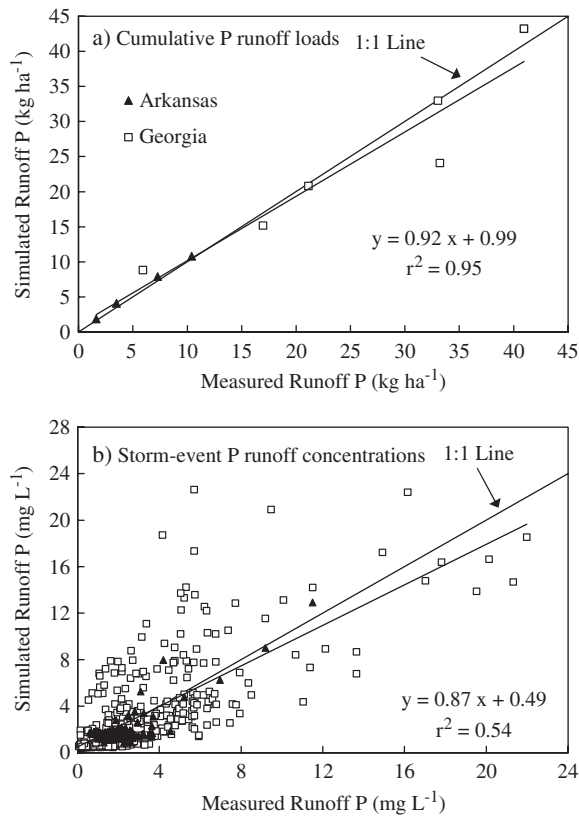


Fig. 5. Measured and simulated results for (a) cumulative P loads in runoff (kg ha^{-1}) and (b) storm event dissolved inorganic P concentrations in runoff (mg L^{-1}) data from the Arkansas and Georgia field studies of Edwards et al. (1996) and Pierson et al. (2001a).

ranging from 32 to 89% of total P loss in runoff. Initial P concentrations in soil were all relatively high because of past manure applications. Grazing cattle manure contributed 11 to 28%, and poultry manure contributed 0 to 55% of total P in runoff. Thus for grazed systems similar to these Arkansas fields, surface application of poultry manure may not dominate P loss in runoff. Better managing poultry manure may reduce nonpoint source P pollution, given that this is likely the source of high soil P concentrations, but soil and grazing will contribute sig-

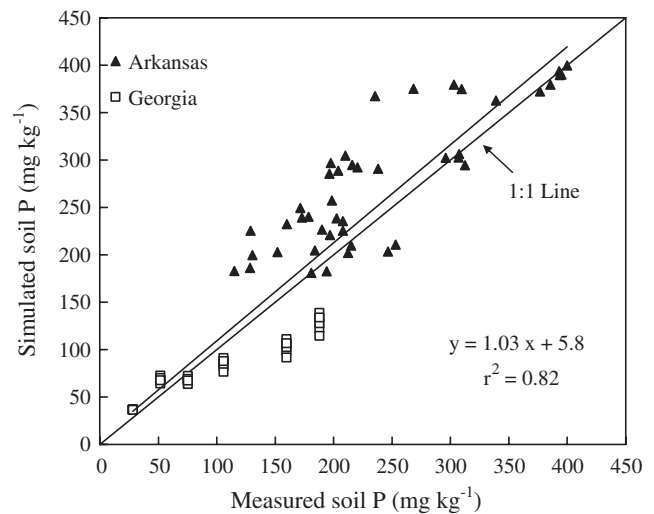


Fig. 6. Measured and simulated results for soil labile P data from the Arkansas and Georgia field studies of Edwards et al. (1996) and Pierson et al. (2001a).

nificant amounts of P to runoff even if poultry manure application ceased. Such a conclusion is in contrast to some field studies investigating the effect of grazing on nutrients in runoff (Sauer et al., 1999; Edwards et al., 2000; Nash et al., 2000). The fact that our model successfully predicted P loss in runoff for all four Arkansas fields that had either grazing alone or combinations of grazing and poultry manure suggests that simulation results would have been less successful had the model predicted less of an impact of grazing animals on P runoff. In the Georgia study where grazing intensity was less, grazing contributed 16% of total simulated P in runoff. Because initial soil P concentrations in Georgia fields (20 mg kg^{-1}) were much less than in Arkansas fields, soil contributed an average of only 9% of total simulated P in runoff, leaving poultry manure as the primary contributor of P to runoff.

This type of data analysis from our model can help producers identify not only how much P is lost in runoff for a set of management conditions, but also what the dominant sources of P are. This in turn can help develop mitigation strategies to target specific sources. For ex-

Table 1. Simulated results for cumulative P loads in runoff from different manure and soil sources from the Arkansas study of Edwards et al. (1996) and the Georgia study of Pierson et al. (2001a).

Field	Field area ha	Initial soil test P mg kg^{-1}	Total runoff cm	Sources of simulated dissolved P in runoff				
				Poultry manure inorganic P	Poultry manure organic P	Cow manure inorganic P	Cow manure organic P	Soil inorganic P
				$\text{g ha}^{-1} \text{ cm runoff}^{-1}$				
Arkansas								
RM	1.23	180.0	51.5	72.9	6.2	56.1	5.6	81.0
RA	0.57	307.0	11.5	—	—	41.7	4.6	118.4
WM	1.06	210.0	16.2	131.9	17.9	33.3	2.9	87.1
WA	1.46	400.0	46.6	—	—	17.3	1.5	151.9
Georgia								
E1	0.75	28.0	28.6	213.8	23.8	58.9	5.2	34.6
E2	0.75	28.0	53.0	221.5	24.7	49.1	4.3	39.9
E3	0.75	28.0	81.6	304.0	37.0	58.4	5.2	41.6
E4	0.75	28.0	58.3	317.2	38.5	60.4	5.2	34.8
E5	0.75	28.0	49.0	326.9	39.6	60.6	5.4	37.0
E6	0.75	28.0	114.0	275.4	30.5	65.6	5.9	37.9

ample, a manager of field WA in Arkansas would know that without poultry manure applications, reducing soil P before changing grazing practices might be more effective in reducing P in runoff, provided grazing practices were not a source of excess soil P. Conversely, a manager of field WM might see that poultry manure management is as critical in the short-term as reducing soil P for controlling P in runoff, while grazing management may be the least concern. Managers of the Georgia fields would have to concentrate on reducing P in runoff from surface-applied poultry manure.

CONCLUSIONS

We have developed and documented a new model that simulates surface application of animal manures, manure dry matter and P transformations through time in unincorporated manures, and direct loss of dissolved P in runoff from unincorporated manures. Our model operates on its own, but is ultimately intended to be incorporated into more complex field- or watershed-scale models, thus rectifying a major weakness of most existing models. We used data from field studies in Georgia and Arkansas to validate our manure P and runoff model. Results show the model successfully simulates changes in surface manure dry matter and P pools through time, dissolved inorganic P concentrations in runoff on a storm-by-storm and long-term load basis, and P in the underlying 2-cm layer of soil. Therefore, our manure and P runoff model represents a potentially important modification for more complex models used to assess the risk of agricultural P loss to the environment. One particular value of our model is that it can help field managers identify which sources of P, be they soil, machine-applied manure, or manure applied from grazing animals, are dominant contributors of P to runoff. This in turn can help target alternative management practices that will be most effective in mitigating P loss.

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