

## Modeling Phosphorus Transfer between Labile and Nonlabile Soil Pools: Updating the EPIC Model

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### ABSTRACT

Phosphorus transfer from agricultural soils to surface waters is an important environmental issue. Commonly used computer models like EPIC have not always been appropriately updated to reflect our improved understanding of soil P transformations and transfer to runoff. Our objectives were to determine if replacing EPIC's constant sorption and desorption rate factor (0.1) with more dynamic rate factors can more accurately predict changes in soil labile P on addition to and depletion of P from soils. From published data, methods were developed to easily determine dynamic sorption and desorption rate constants from soil properties. These methods were tested with data from new soil P incubation experiments where changes in soil labile P after P addition to and depletion from nine U.S. soils were measured. Replacing constant 0.1 P sorption rate factors with dynamic factors improved prediction of soil labile P with time after P additions but more so for high-clay than low-clay soils. EPIC's constant 0.1 P desorption rate factor greatly underpredicted soil P desorption. Increasing the constant to 0.6 improved predictions, whereas dynamic P desorption rate factors most accurately predicted P desorption. Soil P simulations showed that replacing constant P sorption and desorption rate factors with dynamic ones may change dissolved P loads ( $\text{kg ha}^{-1}$ ) in runoff for common soil, cropping, and runoff scenarios by only 1 to 8% in the long term but by 8 to 30% in the short term. These improvements are recommended given the simplicity of making EPIC's sorption and desorption rate factors dynamic.

PHOSPHORUS (P) transfer from agricultural soils to P-limited surface waters can stimulate eutrophication, which limits water use for drinking, recreation, and industry (Bennett et al., 2001; Sharpley et al., 1999). Over the past decade, substantial effort has been put toward eliminating excess inputs of agricultural P to surface waters. Understanding of sources and pathways of P transfer has greatly improved (Gburek et al., 2000; Sims et al., 2000), but computer models used to simulate P transport from agricultural soils to the environment have not always been updated to reflect this improved understanding (Sharpley et al., 2002).

Because they are relatively rapid and cost effective, models such as EPIC (Williams et al., 1983), GLEAMS (Leonard et al., 1987), ANSWERS (Bouraoui and Dillaha, 1996), and SWAT (Arnold et al., 1998) are used to identify agricultural areas in watersheds with a high potential for P transfer to runoff, to quantify the P transfer, and to assess the ability of management prac-

tices to minimize the transfer. Soil P routines in these models were developed from EPIC, often with modifications. Soil P routines in EPIC provide for pools of Active and Labile inorganic P (Jones et al., 1984). Any inorganic P added to soil becomes labile at application but may be quickly transferred to Active P to simulate soil P sorption. When Labile P decreases due to transfer to runoff or plant uptake, P is transferred from the Active to the Labile P pool to simulate soil P buffering. Flow between Labile and Active P is governed by an equilibrium equation with a constant rate factor of  $0.1 \text{ d}^{-1}$ . Because experiments have shown that inorganic P sorption from a labile to a more stable form is initially rapid and slows with time (Indiati et al., 1999; Javid and Rowell, 2002), a constant rate factor may not best simulate soil P sorption dynamics. The 0.1 rate constant for soil P buffering exists in EPIC with no apparent justification.

EPIC was designed to simulate soil erosion and its effects on crop productivity for a variety of soils, climates, crops, and conservation practices. A constant rate of P transfer between Labile and Active P was adequate for these purposes. As the effort to control P transfer from agricultural soils has intensified, EPIC and other models with its soil P routines are used to simulate dissolved and sediment P transfer from soil to runoff (Pierson et al., 2001; Sharpley et al., 2002). Because soil Labile P in such models is the sole source for dissolved P in runoff and contributes to sediment P in runoff, Labile P dynamics must be accurately simulated if a model is to reliably estimate runoff P. Because most annual P transfer from soils can often occur during a few, intense storms (Pionke et al., 1996, 2000), especially after recent additions of P to soils (Shreve et al., 1995), models must accurately simulate short- and long-term soil P dynamics. As the uses of EPIC and other models change, we must examine model routines and determine if they are appropriate for new uses. Our objective was to develop dynamic rate factors to update the constant 0.1 factor controlling P flow between the inorganic Labile and Active P pools for EPIC and other models that use its P routines.

### MATERIALS AND METHODS

#### Description of Phosphorus Subroutines in EPIC

Soil P routines in EPIC provide for pools of Active and Labile inorganic P (Jones et al., 1984). Labile P represents easily desorbable P immediately available for plant uptake or transfer to runoff and is defined as P extracted by anion exchange resin (Sharpley et al., 1984). Model users must input an initial value for Labile P. Active P represents more stable P that is not easily desorbable but is in equilibrium with Labile P. Active P is initialized from Labile P and a P sorption coefficient (PSC) as:

$$\text{Active P} = (\text{LabileP}) (1 - \text{PSC})/\text{PSC} \quad [1]$$

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The PSC represents how much of any inorganic P added to soil remains Labile P on reaching relative equilibrium. A PSC of 0.4 means 40% of added P remains Labile P and 60% becomes Active P. Experimentally, PSC values are determined by measuring Labile P in a soil, adding inorganic P to the soil, incubating the soil for 6 mo, and again measuring Labile P. The percentage of added P that remains Labile is the PSC (Sharpley et al., 1984). Soil PSC can also be estimated from such properties as soil texture, pH, and base saturation for similarly weathered soils (Sharpley et al., 1984, 1989).

When inorganic P is added to soil, the equilibrium between Labile and Active P in Eq. [1] is disrupted. Labile P is relatively too large, and P moves from Labile to Active P to re-establish equilibrium. The amount of P moved daily is:

$$P \text{ Moved} = 0.1 \{ \text{Labile P} - (\text{Active P}) [\text{PSC}/(1 - \text{PSC})] \} \quad [2]$$

The term (Active P) [PSC/(1 - PSC)] calculates what Labile P should be relative to the Active P that has not yet changed. The difference between this relative Labile P and the actual Labile P after P addition is the P imbalance between the pools. Each day, 1/10 of this imbalance is moved from Labile to Active P until the pools reach equilibrium. The 0.1 rate factor is from Rajan and Fox (1972), who observed that P sorption in three soils was curvilinear with time, with 100% sorption occurring in 10 d and a subsequent average of  $0.1 \text{ d}^{-1}$ . In EPIC, whenever Active P is too large relative to Labile P, P moves from Active to Labile P at the same 0.1 rate. As far as we know, there is no documented justification for the 0.1 desorption rate.

### Phosphorus Sorption and Desorption Experiments

Nine soils were collected from Ap horizons in the eastern USA (Table 1). From New York were Honeyoye (fine-loamy, mixed, active, mesic Glossic Hapludalfs), Lewbeach (coarse-loamy, mixed, semiactive, frigid Typic Fragiudepts), and Marden (coarse-loamy, mixed, active, mesic Typic Fragiudepts) soils. From Pennsylvania were Berks (loamy-skeletal, mixed, active, mesic Typic Dystrudepts), Hagerstown (fine, mixed, semiactive, mesic Typic Hapludalfs), and Watson (fine-loamy, mixed, active, mesic Typic Fragiudults) soils. From Vermont were Machia (coarse-loamy over sandy or sandy-skeletal, mixed, frigid Aquic Haplorthods), Allen (fine-loamy, mixed, active, nonacid, mesic Mollic Endoaquepts), and Georgia (coarse-loamy, mixed, semiactive, mesic Aquic Dystric Eutrudepts) soils. All soils were air dried and ground to pass a 2.0-mm sieve.

Triple superphosphate was added to 200 g of each soil at rates of 0, 40, 80, and 120 kg total P ha<sup>-1</sup>. Deionized water was added to achieve a water content of 20% by weight, and soils

**Table 1. Selected properties of the nine eastern U.S. soils used in incubations and extractions to test new sorption and desorption rate factors.**

State	Soil name	Texture	Sand	Silt	Clay	N	C	pH	Mehlich-3P
			%						mg kg <sup>-1</sup>
NY	Honeyoye	Clay loam	38	34	28	0.17	2.23	7.46	65
	Lewbach	Clay loam	34	33	33	0.29	3.35	5.35	169
	Marden	Clay loam	32	37	31	0.23	2.63	5.89	73
PA	Berks	Clay loam	24	45	31	0.23	4.22	4.83	18
	Hagerstown	Silt clay	10	56	34	0.24	2.45	5.74	51
	Watson	Silty clay	16	44	40	0.26	2.80	5.70	52
VT	Machia	Sandy loam	79	8	13	0.14	0.85	6.40	106
	Allen	Clay	12	34	54	0.52	4.99	6.83	154
	Georgia	Loam	42	36	22	0.26	3.11	7.13	177

were incubated at room temperature, with water added periodically to maintain the 20% water content. At 1 d and at 1, 2, 4, 12, and 24 wk, 15- to 20-g subsamples of each soil were collected, air dried, and sieved (2 mm). Iron-oxide strip-extractable P was determined on each sample by shaking 1 g of soil for 16 h with 40 mL of 0.01 M CaCl<sub>2</sub> and one Fe-oxide-coated filter paper strip with an area of 20 cm<sup>2</sup> (Chardon, 2000). The Fe-oxide strip was removed, rinsed in deionized water to remove adhering soil, and shaken for 1 h with 40 mL 0.1 M H<sub>2</sub>SO<sub>4</sub> to desorb P. Phosphorus in the H<sub>2</sub>SO<sub>4</sub> solution was measured colorimetrically (Murphy and Riley, 1962). Iron-oxide strip P was used to estimate Labile P as defined in EPIC, although the Labile P pool in EPIC was originally quantified by anion exchange resin extraction (Sharpley et al., 1984). Because resin and strip extractable P are well correlated to soil labile P as measured by isotopic exchange (Aigner et al., 2002; Schneider and Morel, 2000), Fe-oxide strip P justifiably represents Labile P for EPIC (Vadas and Sims, 2002). By monitoring changes in Fe-oxide strip P throughout the soil incubation, transfer of P from Labile to Active P as simulated in EPIC could be evaluated.

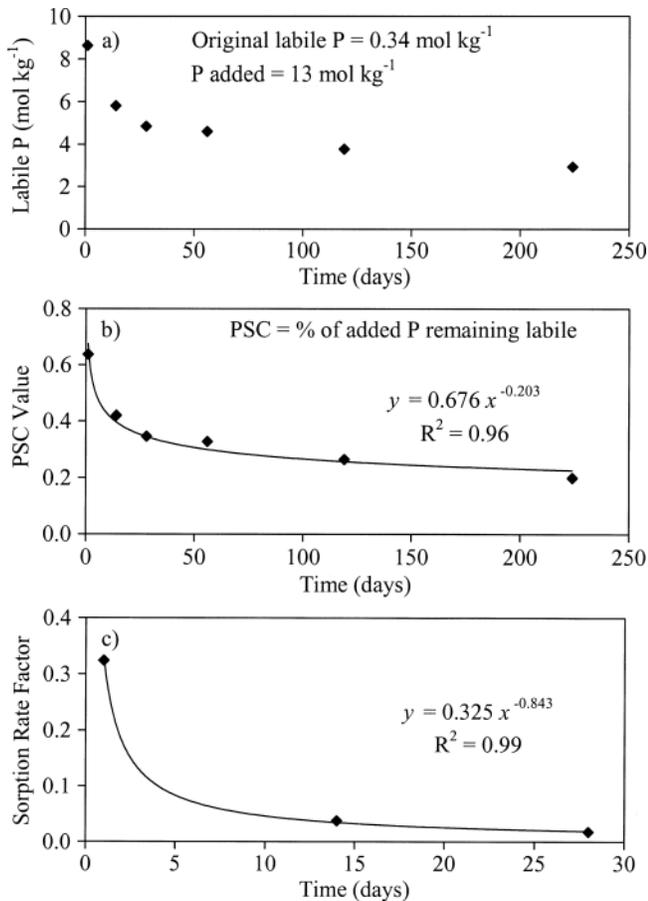
Phosphorus desorption experiments were conducted on selected soils with sequential Fe-oxide strip extractions, as described previously, to simulate P transfer from Active to Labile P pools in EPIC. All nine soils incubated for 12 and 24 wk with P additions of 40, 80, and 120 kg total P ha<sup>-1</sup> were used. One gram of soil was shaken with 40 mL of 0.01 M CaCl<sub>2</sub> and one Fe-oxide strip for 16 h, after which the strip was removed with slow up-and-down movement in the water to remove adhering soil particles. A new strip was added and shaken with soil for 16 h. The strip removal and replacement was repeated for a total of eight sequential extractions, each conducted for 16 h.

### Literature Review and Calculation of Rates of Phosphorous Sorption

Data from P sorption experiments of Indiati et al. (1999), Javid and Rowell (2002), Robinson and Sharpley (1996), Sharpley (1982), Sharpley et al. (1989), and Pautler and Sims (1998) were used to determine rates of P movement from Labile to Active pools as simulated in EPIC. When required data were not published in tables or figures, data were obtained directly from authors. All experiments generally followed the procedure of Sharpley et al. (1984) to determine soil PSC. Inorganic P was added to soils, which were incubated at field capacity for times ranging from 28 to 365 d. Labile P was measured periodically by water extraction (100:1 water/soil ratio for 60 min; Sharpley, 1982), Fe-oxide strip extraction (Indiati et al., 1999; Pautler and Sims, 1998; Robinson and Sharpley, 1996), anion exchange resin extraction (Sharpley et al., 1989), Olsen extraction (Indiati et al., 1999; Javid and Rowell, 2002; Olsen et al., 1954), or Mehlich-3 extraction (Indiati et al., 1999; Mehlich, 1984). This enabled calculation of changes in PSC values with time after P addition to soil.

Experiments showed that when P is added to soil, labile P and subsequent PSC values decrease over time, as shown in Fig. 1a and b for one soil from Pautler and Sims (1998). The decline in PSC values is curvilinear, so that they eventually reach a fairly constant base value. Figure 1b shows that EPIC's constant 0.1 sorption rate factor in Eq. [2] does not reflect the curvilinear decline of soil PSC. Thus, Eq. [2] could be modified to include a dynamic rate factor as:

$$P \text{ Moved} = (\text{dynamic rate factor}) \{ \text{Labile P} - [\text{Active P}] [\text{PSC}(1 - \text{PSC})] \} \quad [3]$$



**Fig. 1.** Example of measured decreases in (a) labile P measured with Fe-oxide strips, and calculated (b) PSC values, and (c) P sorption rate values for one soil of Pautler and Sims (1998).

Using the same soil from Pautler and Sims (1998), the following example illustrates how we calculated dynamic sorption rate factors for data from the six published studies. For each soil sampling time during the incubation, we determined a PSC value as  $([\text{current soil P} - \text{initial soil P}]/\text{P added})$ . Changes in PSC with time were fitted to a power-function curve so that PSC values reached a base value at a relatively large time (Fig. 1b). To be consistent with EPIC, a time of 180 d was inserted for the x-value in the power equation, with the resulting y-value as the final PSC value for the soil, which was 0.236 for data in Fig. 1b. To calculate dynamic sorption rate factors of Eq. [3], a spreadsheet as in Table 2 was made for the same soil of Pautler and Sims (1998). Labile P was arbitrarily initialized to 10.00 on Day 0 and Active P initialized (32.37) with the PSC and Eq. [1]. At the start of Day 1, an arbitrary amount of P (10.00) was added to increase Labile P to 20.00. A relative Labile P was calculated from the yet unchanged Active P (Eq. [1]). The difference between this relative Labile P (10.00) and the actual Labile P after P addition (20.00) was

the imbalance between Labile and Active P (10.00). The PSC for Day 1 was 0.68 (Fig. 1b), so 32.4% (3.24) of the P imbalance was moved to Active P. The dynamic P sorption rate for Eq. [3] for Day 1 was thus 3.24/10.00 or 0.32.

At the next arbitrary time step of Day 14, initial Labile (16.76) and Active P (35.61) were the same as at the end of Day 1. Because the Labile P that would exist relative to this Active P at equilibrium (Eq. [1]) was 11.00, an imbalance of 5.76 remained between Labile and Active P. The PSC for Day 14 had decreased to 0.40, so the original P added of  $10.00 \times (1 - 0.40)$ , or 6.04, was the cumulative amount of added P that should be moved to Active P between the end of Day 1 and the end of Day 14, or 13 d. Because 3.24 was already moved on Day 1, that left  $6.04 - 3.24$ , or 2.80, to move from Labile P to Active P over these 13 d. The sorption rate factor for Day 14 was thus  $(2.80/5.76)/13$ , or 0.04. We repeated this procedure to generate sorption rate factors to 28 d.

For all data, sorption rate factors decreased curvilinearly with time and could be fitted with power equations so they reached base values at large times (Fig. 1c). Using 28 d as total cumulative time ensured that the Y-intercept of the power equation agreed well with the value for the sorption rate factor for Day 1 in Table 2. Thus, the change in sorption rate factors with time was described as:

$$\text{Sorption Rate Factor} = (A) (\text{Time [days]}^B) \quad [4]$$

where Time is the cumulative number of days since the Labile P pool increased and created an imbalance with the Active P pool. Data from the six published studies show that A and B parameters were related to each other with the equation (Fig. 2a):

$$B = -0.238 \text{ Ln}(A) - 1.126 \quad [5]$$

Figure 2c shows that A variables were related to PSC variables with the equation:

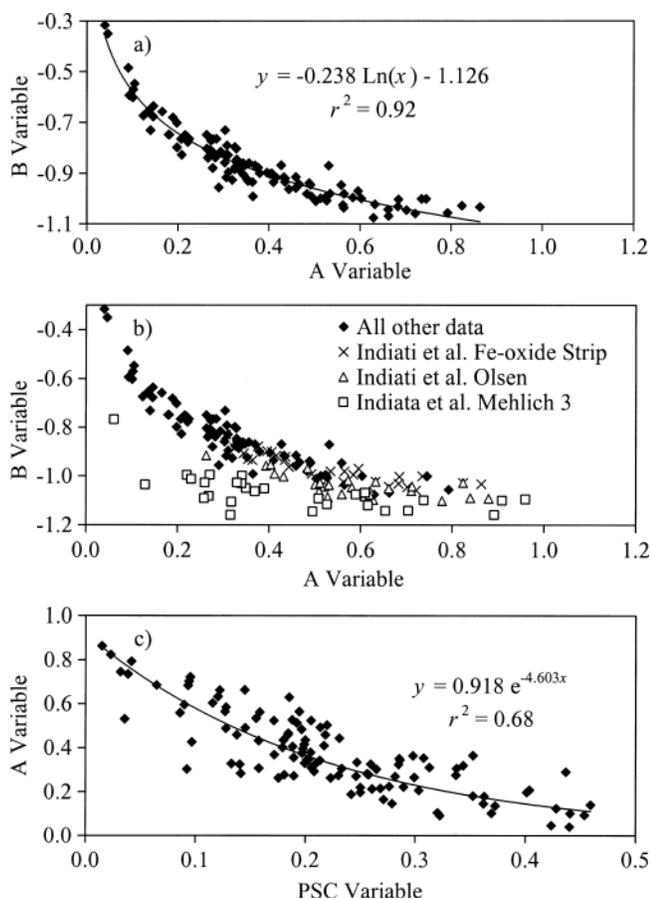
$$A = 0.918 e^{-4.603 \text{ PSC}} \quad [6]$$

Equations [5] and [6] show that as PSC decreases, A increases, and sorption rate factors in Eq. [4] increase. Thus, P is less labile in soil over time. As PSC increases, the opposite occurs. These trends are consistent with the concept of the PSC variable. Using Eq. [4], [5], and [6], dynamic P sorption rate factors from Indiati et al. (1999), Javid and Rowell (2002), Robinson and Sharpley (1996), Sharpley (1982), and Sharpley et al. (1989), and Pautler and Sims (1998) ranged from 0.04 to 0.84 for the first day after P addition to soils. Long-term rate factors were typically about 0.004. These values vary considerably from EPIC's constant 0.1 sorption rate factor.

Consistent relationships in Fig. 2a and 2c show variations in experimental protocols of the six published studies had little effect on dynamic sorption rate factors. In the published experiments, soil P was measured by Olsen extraction, water extraction, anion exchange resin extraction, and Fe-oxide strips, all of which measure soil P through desorption or mild dissolution reactions. Figures 2a and 2c suggest that any of these methods reliably estimate soil labile P, at least when determining sorption rate factors for EPIC. However, other soil extractants were not as appropriate for estimating soil

**Table 2.** Example of the procedure used to determine daily dynamic P sorption rate factors for data of Indiati et al. (1999), Javid and Rowell (2002), Robinson and Sharpley (1996), Sharpley (1982), Sharpley et al. (1989), and Pautler and Sims (1998).

Day	PSC value	Labile P	Active P	Relative labile P	P imbalance	P moved	Sorption rate factor	Cumulative P moved
0		10.00	32.37	10.00				
1 (start)		20.00	32.37	10.00	10.00			
1 (end)	0.68	16.76	35.61	11.00	5.76	3.24	0.32	3.24
14	0.40	13.96	38.42	11.87	2.09	2.8	0.04	6.04
28	0.34	13.44	38.94	12.06	1.41	0.52	0.02	6.56



**Fig. 2.** For soils of Indiati et al. (1999), Javid and Rowell (2002), Robinson and Sharpley (1996), Sharpley (1982), Sharpley et al. (1989), and Pautler and Sims (1998), relationship between (a) calculated A and B values where only labile P is measured, or (b) where labile, Olsen, and Mehlich-3 P are measured. (c) Relationship between calculated A and PSC values.

labile P. For example, Indiati et al. (1999) measured soil P with Fe-oxide strips, Olsen extractant, and Mehlich-3 extractant, which more rigorously dissolves P from soil. Relationships between A and B variables changed slightly when soil P was estimated by Olsen extraction but much more when estimated by Mehlich-3 (Fig. 2b). There was a similar deviation for the relationship between A and PSC values (data not shown). Data from Javid and Rowell (2002) did not show any deviation of the A and B relationship when using the Olsen extractant (Fig. 2b). Because soils of Javid and Rowell (2002) were all greater than pH 7.2 and many of the soils of Indiati et al. (1999) were acid soils, the Olsen extractant may more poorly estimate labile P in acid soils.

The ability of Eq. [3]–[6] to predict Labile P in soils with time after a P addition was tested using data from our soil incubations. An example of the calculations used to predict Labile P is presented in Table 3 for one of our soils. A PSC of 0.28 was calculated from soil clay content (Sharpley et al., 1984), and variables A and B from Eq. [5] and [6] were used to determine daily sorption rate factors for Eq. [3]. Initial Labile P estimated by Fe-oxide strip extraction was 7.7 mg kg<sup>-1</sup>, and initial Active P was 19.63 (Eq. [1]). For this soil, 50 mg kg<sup>-1</sup> of P was added on Day 1. It was assumed this P went entirely to Labile P, and the P imbalance between Active P and Labile P before any P movement was calculated with Eq. [3]. This P imbalance was multiplied by the sorption rate factor for Day 1

**Table 3.** Example of the procedure used to predict changes in soil Labile P after a P addition to one soil used in our incubation experiments.

Day	Labile P	Active P	P imbalance	Sorption rate factor	P moved
0	7.70	19.63	0.00	—	—
1	57.70	19.63	50.00	0.25	12.45
2	45.25	32.08	32.66	0.14	4.68
84	23.78	53.55	2.78	0.01	0.02
85	23.76	53.57	2.75	0.01	0.02

to determine how much P to move from Labile to Active P. This procedure was repeated to predict Labile P through time (Table 3). Iron-oxide strip P measured at each incubation time of 1 d, and 1, 2, 4, 12, and 24 wk was compared with Labile P predicted at each time.

### Literature Review and Calculation of Rates of Phosphorus Desorption

In EPIC, P transfer from Active to Labile P is calculated with Eq. [2] and a constant 0.1 rate factor. To develop a more dynamic desorption rate factor, data from P desorption experiments of Indiati (1998), Indiati and Sharpley (1996), Maguire et al. (2000), McDowell and Sharpley (2002), Sharpley (1996), and Siddique and Robinson (2004) were used. When required data were not published in tables or figures, data were obtained directly from authors. The experiments involved sequential Fe-oxide strip or anion exchange membrane soil extractions similar to the ones conducted for our incubated soils.

Table 4 shows the procedure used to calculate dynamic desorption rate factors for one soil of Sharpley (1996). It was assumed that P extracted by the first Fe-oxide strip represented initial Labile P (78.00). A PSC was calculated based on soil clay content (Sharpley et al., 1984) and initial Active P (311.07) calculated with Eq. [1]. A P imbalance (78.00) between Active and Labile P was then calculated with Eq. [3] and the assumption that Labile P was 0.0 after the first Fe-oxide strip extraction. Assuming that Fe-oxide strips always extracted all Labile P, the P imbalance was multiplied by a fraction less than 1.0, which was the desorption rate factor (0.55 for Day 1), to make P moved from Active to Labile P for Day 1 (42.90) approximately equal to Fe-oxide strip P on Day 2 (43.09) (Fig. 3a). Following this procedure, desorption rate factors decreased curvilinearly with time, which could be described by power equations (Fig. 3b). Base values in power equations for all four studies were well related to soil PSC values (Fig. 3c) by the equation:

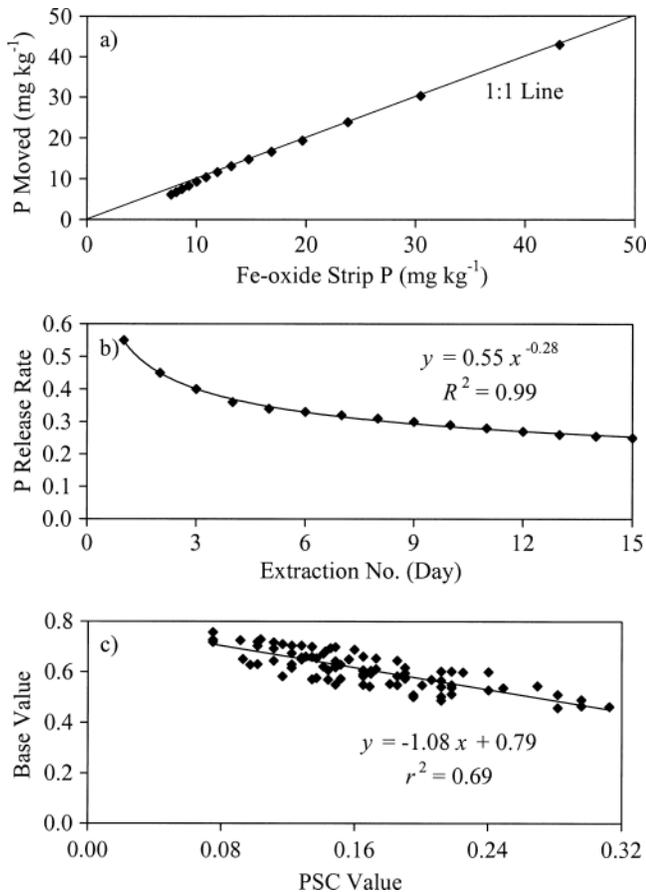
$$\text{Base} = -1.08 (\text{PSC}) + 0.79 \quad [7]$$

However, no similar relationships with power equation exponent values were observed, which ranged from  $-0.60$  to  $-0.07$  and averaged  $-0.29$ .

To test this method of determining desorption rate factors and predicting P transfer from the Active to Labile P, data from our P desorption experiments of sequential Fe-oxide strip

**Table 4.** Example of the procedure used to calculate dynamic desorption rate factors for one soil of Sharpley (1996).

Extraction no. (day)	Fe-Oxide strip P	Initial active P	P imbalance	Desorption rate factor	P moved	Final active P
1	78.00	311.07	78.00	0.55	42.90	268.17
2	43.09	268.17	67.24	0.45	30.26	237.91
3	30.46	237.91	59.66	0.40	23.86	214.05
14	8.15	96.31	24.15	0.26	6.16	90.15
15	7.68	90.15	22.60	0.25	5.65	84.50



**Fig. 3.** Examples of (a) the method used to match predicted P moved from Active to Labile P to measured sequentially extracted Fe-oxide strip P and (b) the decline in calculated P desorption rate factors for one soil of Sharpley (1996). (c) Relationship between soil PSC values and calculated base values in exponential equations describing decreases in P desorption rate factors with time for data of Indiati (1998), Indiati and Sharpley (1996), Maguire et al. (2000), McDowell and Sharpley (2002), Sharpley (1996), and Siddique and Robinson (2004).

extractions were used. The same procedure as described previously was used to determine desorption rate factors (Table 4), except that we calculated daily rate factors using the equation:

$$\text{Desorption Rate Factor} = (\text{Base}) (\text{Time} [\text{days}]^{-0.29}) \quad [8]$$

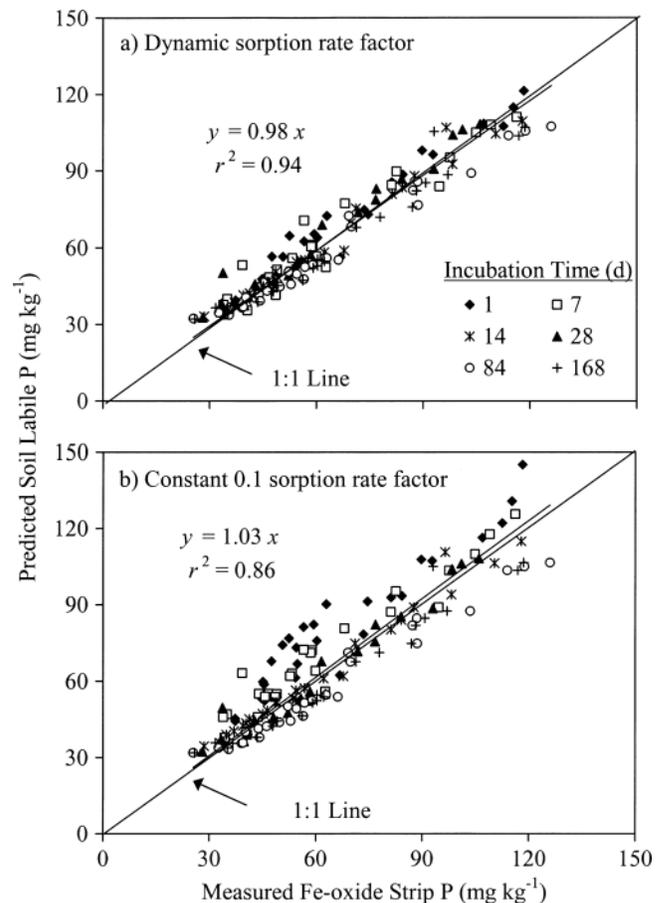
Initial Active P was predicted by the soil P sorption procedure described previously and shown in Table 2 rather than based on initial Labile P and soil PSC with Eq. [1]. Base values in power equations were calculated from soil PSC with Eq. [7] and exponents set equal to the average of  $-0.29$ , as described previously. Predicted P moved from Active to Labile P was then compared for a given day to Fe-oxide strip P for the subsequent day (Table 4).

## RESULTS AND DISCUSSION

### Phosphorus Sorption Rate Factor

For our soil incubations, dynamic sorption rate factors predicted Labile P after various P additions and

incubation times very well (Fig. 4a). EPIC's constant 0.1 rate factor also reliably predicted Labile P (Fig. 4b) but with overpredictions at early incubation times. This was truer for high clay soils than low clay soils because initial sorption rate factors for high clay soils were much greater than 0.1 (Eq. [4]–[6]), and P transfer from Labile to Active P was greater. Over longer times, dynamic and constant 0.1 sorption rate factors predict similar Labile P. For low clay soils, initial P sorption rate factors were close to 0.1, and P transfer from Labile to Active P was similar when using dynamic or constant 0.1 rate factors. Therefore, dynamic P sorption rate factors improve prediction of Labile P for many soil types but more so for high clay than low clay soils. For example, at 1 d of incubation, predicted Labile P averaged the same as measured Fe-oxide strip P using dynamic sorption rate factors but averaged 23% greater than Fe-oxide strip P when using 0.1 rate factors. However, overprediction with the 0.1 factor averaged only 13% for soils with clay content less than  $250 \text{ g kg}^{-1}$  but averaged 28% for soils with clay content greater than  $250 \text{ g kg}^{-1}$ . In models such as EPIC, this could translate into an average overestimation of dissolved P in runoff P of 36% for soils with clay contents greater than  $250 \text{ g kg}^{-1}$  during the first few days after a P addition of  $50 \text{ mg kg}^{-1}$ .



**Fig. 4.** For nine soils from the Eastern USA subjected to various P additions and incubation times, the relationship between measured Fe-oxide strip P and predicted soil labile P using (a) dynamic or (b) constant 0.1 sorption rate factors.

## Phosphorus Desorption Rate Factor

Using data from our sequential Fe-oxide strip extractions, EPIC's constant 0.1 P desorption rate factor greatly underestimated P transfer from Active to Labile P (Fig. 5a). Increasing the constant to 0.6 improved predictions (Fig. 5b), but dynamic P desorption rate factor most accurately predicted P transfer from Active to Labile P (Fig. 5c). EPIC's 0.1 desorption rate factor should at least be adjusted to 0.6 and even to dynamic values.

Dynamic desorption rate factors ranged from 0.44 to 0.69 for the first Fe-oxide strip extraction and consistently declined to about 0.32 for the last extraction. Therefore, even a constant 0.6 desorption rate factor does not capture this variability in the rate of soil P desorption. For high clay soils, initial dynamic P desorption rate factors can be greater than 0.6 (Eq. [7]), and P transfer from Active to Labile P is greater. Afterward, dynamic desorption rate factors become less than 0.6, and P transfer from Active to Labile P is less. For low clay soils, dynamic desorption rate factors are always less than 0.6, so P transfer from Active to Labile P is less. However, the difference in P transfer between the two rate factors narrows and eventually inverts as time increases. This is because the imbalance between Active and Labile P decreases faster with the constant

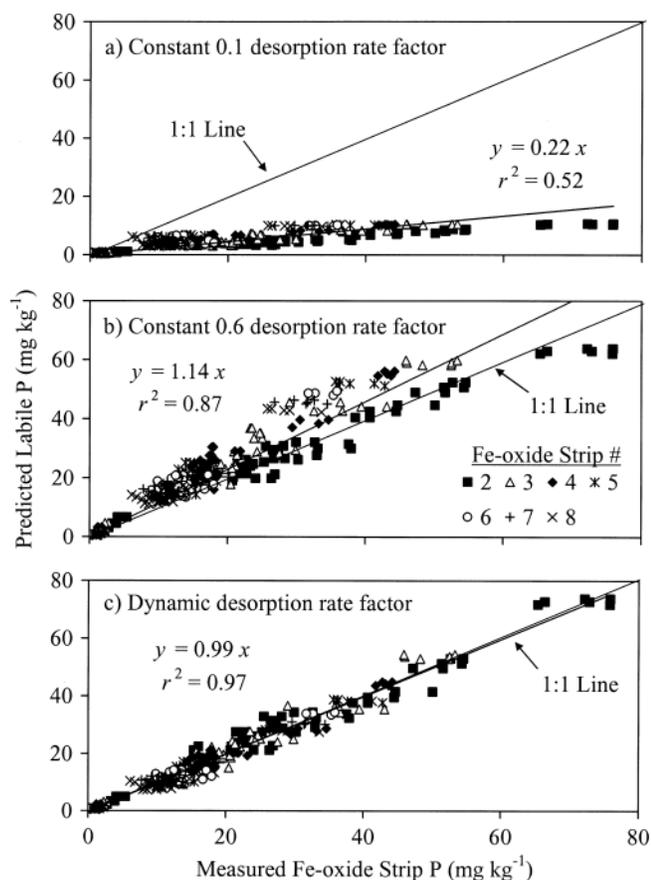


Fig. 5. For nine soils from the Eastern USA subjected to various P additions and incubation times, the relationship between measured sequentially extracted Fe-oxide strip P and predicted soil labile P using (a) constant 0.1, (b) constant 0.6, or (c) dynamic desorption rate factors.

0.6 rate factor, even though the rate of P transfer remains greater. The same trend is true for high clay soils, but after longer times. Therefore, using constant 0.6 rate factors for low clay soils may overestimate short-term P desorption by 20 to 30% but underestimate long-term P desorption by 50 to 60%. The same is true for high clay soils, but with an initial underestimation of P desorption of 5 to 10%.

## Implications of Dynamic Phosphorus Sorption and Desorption Rate Factors

In EPIC, the source of dissolved P transfer in surface runoff is Labile P. An important aspect of dynamic P sorption and desorption rate factors is how they affect predictions of P in runoff. We constructed a simple spreadsheet to broadly quantify the effect of dynamic rate factors on predicted dissolved P loads ( $\text{kg ha}^{-1}$ ) in runoff. We simulated two soil types: high ( $540 \text{ g kg}^{-1}$ ) and low clay ( $130 \text{ g kg}^{-1}$ ). We initialized soil Labile P to  $50 \text{ mg kg}^{-1}$ , calculated PSC from soil clay content (Sharpley et al., 1984), and initialized Active P with Eq. [1]. Three scenarios of crop P uptake and fertilization were simulated: i) crop P uptake at  $150 \text{ mg kg}^{-1}$  over 200 d and P fertilization at  $100 \text{ mg kg}^{-1}$  at the first day of crop growth, ii) crop uptake at  $100 \text{ mg kg}^{-1}$  and fertilization at  $100 \text{ mg kg}^{-1}$ , and iii) crop uptake at  $50 \text{ mg kg}^{-1}$  and fertilization at  $100 \text{ mg kg}^{-1}$ . These scenarios were simulated for two 365-d cycles of crop growth and fertilization. Phosphorus transfer between Active and Labile P was simulated using three scenarios of P desorption and sorption rate factors: (i) EPIC's constant 0.1 desorption and sorption rate factors, (ii) constant 0.1 P sorption and 0.6 desorption rate factors, and (iii) dynamic rate factors. We randomly chose 36 d per cycle for runoff and Labile P transfer to runoff to occur. Dissolved P in runoff ( $\text{mg L}^{-1}$ ) was calculated from Labile P and a constant extraction coefficient of 0.005 (Vadas et al., 2005b). Runoff randomly varied between 0.5 and 1.2 cm, which is in a range measured from natural rainfall over 14 mo at a research site in central PA (P.A. Vadas, unpublished data, 2005). Phosphorus loads in runoff ( $\text{kg ha}^{-1}$ ) were calculated on an arbitrary field size of 1 ha, and total runoff P loads were summed over the entire simulation.

Variations in P sorption and desorption rate factors did not drastically change predicted dissolved P loads in runoff over the entire 2-yr simulation cycle (Table 5). For low and high clay soils, the difference in dissolved P loads between constant 0.1 and dynamic factors was 1 to 3%. The difference in P loads between constant 0.1 to 0.6 and dynamic factors was 1 to 3% for the low clay soil and 5 to 8% for the high clay soil. Predicted runoff P was greatest with constant 0.1 to 0.6 rate factors essentially because they transferred the least P from Labile to Active P after fertilization and the most P from Active to Labile P during crop uptake (Table 4). For the high clay soil, runoff P was least with dynamic rate factors because they transferred P fastest from Labile to Active P after fertilizer P addition. For the low clay soil, runoff P was least with constant 0.1 rate factors essentially because

**Table 5. Simulated P loads in runoff for various cropping and fertilization scenarios and combinations of P sorption and desorption rate factors. Numbers in parentheses are P runoff loads for the first 30 d after fertilization.**

Soil type†	P load in runoff		
	Constant 0.1 rate factors	Constant 0.1 and 0.6 rate factors	Dynamic rate factors
	kg ha <sup>-1</sup>		
	<u>Excess crop P uptake</u>		
High clay	1.12 (0.26)	1.20 (0.26)	1.11 (0.20)
Low clay	1.08 (0.27)	1.14 (0.27)	1.11 (0.25)
	<u>Equal crop P uptake and fertilization</u>		
High clay	1.27 (0.27)	1.32 (0.27)	1.24 (0.21)
Low clay	1.38 (0.29)	1.42 (0.29)	1.39 (0.27)
	<u>Excess P fertilization</u>		
High clay	1.41 (0.27)	1.44 (0.27)	1.37 (0.21)
	1.67 (0.30)	1.69 (0.30)	1.68 (0.28)

† High clay is 5.4 g clay kg<sup>-1</sup> soil; low clay is 1.3 g clay kg<sup>-1</sup> soil.

they transferred the least P from Active to Labile P during crop P uptake.

An important distinction between dynamic and constant P sorption and desorption rate factors is predicted P loads in runoff for the first 30 d after P fertilization (Table 5). For the low clay soil, predicted runoff P was 7 to 8% greater using constant rate factors compared with dynamic rate factors. For the high clay soil, however, constant rate factors predicted 30% more P in runoff than dynamic rate factors. This is because P transfer from Labile to Active P was greater with dynamic rate factors in the periods after P fertilization, with a greater difference for the high clay soil than the low clay soil.

## CONCLUSIONS

Phosphorus (P) transfer from agricultural soils to surface waters continues to be an important environmental water quality issue. Although extensive research over the past two decades has improved understanding of P transport pathways, computer models used to simulate P transport have not always been appropriately updated. Because soil P routines in many current models are based on those of EPIC, we conducted literature reviews and soil P sorption and desorption experiments to modify EPIC's constant 0.1 sorption and desorption rate factors to more accurately predict changes in soil labile P on addition to and depletion of P from soils. More accurate labile P predictions mean more accurate predictions of dissolved P transfer from soil to surface runoff.

In comparison with Labile P measured during soil P incubations, dynamic P sorption rate factors more accurately predicted soil Labile P with time after P addition than EPIC's constant 0.1 rate factors. Constant 0.1 rate factors overpredicted Labile P in the first few days and weeks after a P additions, and this overprediction was more pronounced for high-clay (>250 g kg<sup>-1</sup>) than low-clay (<250 g kg<sup>-1</sup>) soils. This can translate into an overprediction of dissolved P in runoff by as much as 36% for soils with clay contents greater than 250 g kg<sup>-1</sup> during the first few days after a P application.

EPIC's constant 0.1 P desorption rate factor greatly underestimated P transfer from Active to Labile P.

Increasing the constant to 0.6 improved predictions, but dynamic P desorption rate factors most accurately predicted P transfer from Active to Labile P. Constant 0.6 desorption rate factors for low clay soils may overestimate short-term P transfer from Active to Labile P by 20 to 30% but underestimate long-term P transfer by 50 to 60%. The same is true for high clay soils, but with an initial underestimation of P transfer of 5 to 10%.

Replacing constant soil P sorption and desorption rate factors with more dynamic ones in the P-cycling submodel of EPIC may not drastically change long-term estimated dissolved P loads in runoff for situations where P fertilizer is incorporated into soil under common soil, cropping, and runoff scenarios. The difference in runoff P between constant 0.1 or constant 0.1 to 0.6 rate factors and dynamic rate factors may vary from only 1 to 3% for low-clay soils and from 5 to 8% for high-clay soils. However, compared with dynamic P sorption rate factors, EPIC's constant 0.1 sorption rate factor may predict short-term runoff P that is 7 to 8% greater for low-clay soils and 30% greater for high-clay soils. Such runoff P estimations apply to P transfers in soil and not to P transfers in surface applications of P where contact with soil is limited. Vadas et al. (2004, 2005a) have proposed a model to predict P in runoff from surface applied P sources, such as manures. Overall, given the simplicity of changing EPIC's current constant 0.1 sorption and desorption rate factor to dynamic factors, these changes are recommended to achieve more mechanistically valid simulations and better predictions.

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