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Impact of Soil Amendments on Reducing Phosphorus Losses from Runoff in Sod

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ABSTRACT

Research was initiated to study the interaction between soil amendments (lime, gypsum, and ferrous sulfate) and dissolved molybdate reactive phosphorus [$RP_{(<0.45)}$] losses from manure applications from concentrated runoff flow through a sod surface. Four run-over boxes (2.2-m^2 surface area) were prepared for each treatment with a bermudagrass [*Cynodon dactylon* (L.) Pers.] sod surface (using sod blocks) and composted dairy manure was surface-applied at rates of 0, 4.5, 9, or 13.5 Mg ha^{-1}. The three soil amendments were then applied to the boxes. Two 30-min runoff events were conducted and runoff water was collected at 10-min intervals and analyzed for $RP_{(<0.45)}$. Results indicated that the addition of ferrous sulfate was very effective at reducing the level of $RP_{(<0.45)}$. in runoff water, reducing $RP_{(<0.45)}$ from 1.3 mg L^{-1} for the highest compost rate with no amendment to 0.2 mg L^{-1} for the ferrous sulfate in the first 10 min of runoff. Lime and gypsum showed a small impact on reducing $RP_{(<0.45)}$, with a reduction in the first 10 min to 0.9 and 0.8 mg L^{-1}, respectively. The ferrous sulfate reduced the $RP_{(<0.45)}$ in the tank at the end of the first runoff event by 66.3% compared with no amendment. In the second runoff event, the ferrous sulfate was very effective at reducing $RP_{(<0.45)}$ in runoff, with no significant differences in $RP_{(<0.45)}$ with application of 13.5 Mg ha^{-1} compost compared with no manure application. The results indicate that the addition of ferrous sulfate may greatly reduce $RP_{(<0.45)}$ losses in runoff and has considerable potential to be used on pasture, turfgrass, and filter strips to reduce the initial $RP_{(<0.45)}$ losses from manure application to the environment.

Animal waste has traditionally been used in agriculture fields because manure application represents an excellent means of both improving soil physical conditions and providing needed plant nutrients. However, the ratio between N and P in manure is narrower than the amount required for plant production, resulting in an overapplication of P when applied at rates to meet plant N requirements. In addition, the application of solid manure is predominately made to the soil surface and is commonly applied to pastures with no tillage operations.

Laboratory studies have shown that the addition of compounds containing Al, Fe, or Ca can reduce water-soluble P, and thus potentially reduce P release to the environment (Moore and Miller, 1994; Anderson et al., 1995; Stout et al., 1998; Dao, 1999; Dou et al., 2003; Kalbasi and Karthikeyan, 2004). Soluble P will react with Al, Ca, or Fe in soil to form insoluble compounds. For example, insoluble minerals such as hydroxyapatite and fluorapatite will form with Ca, variscite with Al, and strengite with Fe. Kalbasi and Karthikeyan (2004) reported that the application to soil of Al- or Fe-treated dairy manure decreased both soluble and plant-available P. Moore and Miller (1994) reported a reduction in water-soluble P from >2000 mg P kg $^{-1}$ of manure to <1 mg P kg $^{-1}$ with the addition of alum, quick lime, slaked lime, ferrous chloride, ferric chloride, ferrous sulfate, and ferric sulfate to poultry litter under favorable pH conditions. Dao (1999) reported a 50, 83, and 93% reduction in water-extractable P in composted feedlot manure from the addition of gypsum, caliche, and alum, respectively. Dou et al. (2003) found an 80 to 99% reduction and 50 to 60% reduction in P solubility of manure from alum and fluidized bed combustion fly ash, respectively. Likewise, Anderson et al. (1995) reported that gypsum application to dairy manure–amended soils reduced soluble P from 40 to 60%. Dao et al. (2001) reported that the soluble P in manure was reduce by 39% with Al-based by-products and by 48% with Fe-based by-products.

Three products that are particularly promising as amendments for reducing P losses in the environment are gypsum ($CaSO_4$), ferrous sulfate ($FeSO_4 \cdot 7H_2O$), and lime ($CaCO_3$) because they are either readily available for agriculture application or they are waste products themselves. For example, lime is commonly used in agriculture to control soil pH, and caliche (the primary component of which is $CaCO_3$) is commonly found in calcic layers of soils of the western United States. Gypsum is produced in large quantities as a result of air pollution control from coal burning power plants as part of the flue gas desulfurization systems. According to the American Coal Ash Association's coal combustion product production and use survey, 10 349 000 Mg of synthetic gypsum was produced in 2002, with approximately 1% of this utilized for agriculture (American Coal Ash Association, 2004). The compound iron sulfate is commonly used in water treatment plants as a flocculent, and the residuals from the water treatment are generated in large quantities that require disposal. Application to agricultural land of the water treatment residual (WTR) has been suggested as a disposal method (Butkus et al., 1998; Gallimore et al., 1999) to improve agriculture plant production. Research has indicated that the most important limitation to using WTR as a soil amendment to improve plant production is that it ties up plant-available P (Rengasamy et al., 1980; Elliot et al., 1990; Jonasson, 1996; Butkus et al., 1998). The application of WTR to soils or manure with excess soluble P could provide an exemplary alternative to landfilling the WTR.

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Abbreviations: $RP_{(<0.45)}$, dissolved molybdate reactive phosphorus filtered through a 0.45-μm membrane.

With the application of manure to the sod surface, the interaction between the manure and runoff water as it moves through the grass thatch layer is of primary importance. The thatch layer, defined as the accumulation of living and dead grass leaves, stems, and organic debris between the soil surface and the green vegetation (Holt, 1969), will catch and hold the manure. This mechanism greatly reduces the amount of manure that leaves the field as particles but can also increase the amount of interaction that the runoff water has with the surface area of the manure. Research has demonstrated that the thatch layer can potentially alter the movement of fungicides (Dell et al., 1994) and insecticide (Niemczyk et al., 1988) and reduce the potential for these compounds to move off site. Other research has demonstrated that vegetative filter strips can be very effective at reducing pollutants from runoff (Dillaha et al., 1989; Chaubey et al., 1995; Srivastava et al., 1996). However, the effectiveness of buffer strips may be significantly decreased when the concentrated flow pattern of water develops (Chaubey et al., 1995). In a rainfall simulation study, Torbert et al. (1999) reported that with fertilizer application to pasture sod, there appeared to be a mechanism other than infiltration that maintained the concentration of nutrients in runoff above that observed in the conventional- and conservation-tilled soil surface. The focus of this research was to examine the impact of water moving through the thatch layer of a sod and whether the addition of chemical amendments could also intercept soluble P moving through the thatch layer to reduce the amount of soluble P movement downstream.

A greenhouse study was initiated to examine the potential benefits of adding chemical amendments to reduce $RP_{(<0.45)}$ losses from animal manure applications in runoff water. The study examined the interaction between the soil amendments and concentrated surface water flow through the grass thatch layer as it relates to $RP_{(<0.45)}$ transport. Two different experiments were conducted congruently to examine different aspects of this interaction. The objective of the first part was to examine the potential impact of using chemical amendments at the same time as the manure application to reduce the immediate $RP_{(<0.45)}$ losses in runoff observed with the initial runoff event. In many cases, the impact of the first runoff event following manure application will overwhelm all other aspects of P loss potential (Sharpley and Tunney, 2000) and the P contribution from subsequent runoff events is reduced (Kleinman and Sharpley, 2003). The goal of this part of the study was to examine the potential of different chemical amendments to diminish this immediate impact. The objective of the second part of the study was to examine the potential of the chemical amendments to maintain any $RP_{(<0.45)}$ reduction over subsequent runoff events.

MATERIALS AND METHODS

Run-Over Boxes

Four wooden run-over boxes with 0.6- × 3.7-m dimensions (2.2-m^2 surface area) and 60-cm depth, were constructed in a greenhouse and fitted with water dispersion devices, which provided an even distribution of water runoff rate equivalent to 124 mm h^{-1}. The boxes were prepared with a bermudagrass sod surface using commercially prepared sod blocks, with 30 cm of the box used to hold soil under the sod surface and 30 cm of the box above the level of the grass to direct the flow of water across the grass sod surface. The boxes were filled with an Austin clay soil (fine-silty carbonatic, thermic, Udorthentic Haplustolls). The run-over boxes were set at a 5% slope and were designed to examine the concentrated flow of runoff water. McDowell and Sharpley (2002) successfully used runoff boxes to evaluate overland flow of water for P transport across different soil types, and Kleinman et al. (2004) evaluated packed soil boxes and demonstrated that they could be used comparatively between small box and field plot data for evaluation of P transport in surface runoff. The sealed boxes were fitted with drainage holes along the length and water leachate was collected. To measure water runoff rates, runoff water was routed to a 379-L tank, which was continuously weighed and recorded at 1-min intervals. Runoff events lasting 30 min were conducted to measure the effect of chemical amendments on reducing runoff losses of P.

Treatment Application and Sample Analysis

Before each treatment application, a short runoff event was initiated (10 min) and runoff water was sampled for background levels. This was followed by the application of composted dairy manure and gypsum, lime, or ferrous sulfate at the appropriate rates. The composted dairy manure (stored in a dry shed) was applied across the entire sod surface at application rates corresponding to 0, 4.5, 9, and 13.5 Mg ha^{-1}. Following the manure application, the gypsum, lime, or ferrous sulfate (in powder form) was then applied to the entire sod surface at the rate that provided either Fe or Ca at an amount equivalent to the molar P content of the manure at the highest application rate (280 kg ha^{-1} gypsum, 206 kg ha^{-1} lime, 400 kg ha^{-1} ferrous sulfate). Shortly following the application of the treatments, runoff was initiated and water samples were collected at 10-min intervals during the runoff event. A sample at 40 min was also collected as the run-over boxes continued to produce surface drainage. After surface runoff had stopped, a water sample was also collected from the tank to represent the total catch.

Following the first runoff event, a second study was conducted, in which after a 24-h rest period, another 30-min runoff event was conducted. In this study, additional amendment material was added to the boxes receiving 9 and 13.5 Mg ha^{-1} manure so that all of the treatments received three times the molar content of P in the manure. As in the first runoff event, runoff water samples were collected at 10-min intervals during the runoff event and at 40 min as the boxes continued surface drainage. Again, after surface runoff had stopped, a water sample of the catch tank was also collected. Following the second treatment and runoff event, the grass sod and underlying soil was removed and replaced before another runoff event was conducted.

Immediately after collection, water samples were acidified with concentrated HCl and frozen until analyzed. Water samples were filtered through a 0.45-μm membrane and analyzed for PO_4–P using the molybdenum-blue method for P in water (Pote and Daniel, 2000) with a Technicon Autoanalyzer IIC (Seal Analytical, Buffalo Grove, IL). In this manuscript, dissolved molybdate reactive phosphorus will be referred to as $RP_{(<0.45)}$ (Haygarth and Sharpley, 2000).

Samples of the composted dairy manure were collected at the time of application and chemical analyses were conducted for total N, P, K, Ca, Mg, and micronutrient concentrations

Table 1. Composted dairy manure characteristics on a dry-weight basis.

	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn	B	Co	Moisture
	g kg^{-1}					mg kg^{-1}						g 100 g^{-1}
Manure	11.7	4.54	13.7	95.8	5.4	41	5077	216	96	50	5	6.5

by the Soil Testing Laboratory, Auburn University, using procedures outlined by Hue and Evans (1986). Results are reported in Table 1.

Statistical Analysis

Statistical analysis was performed using the Mixed procedure of the Statistical Analysis System (Littell et al., 1996). The study was a split-plot design replicated four times with main plots as manure rates and chemical amendments as subplots. A significance level of $\alpha < 0.05$ was established a priori. The first runoff event statistical analysis was conducted by developing regression equations of $RP_{(<0.45)}$ concentration in runoff water vs. composted dairy manure application rate for each chemical amendment at 10-, 20-, 30-, and 40-min sampling times. The r^2 values reported are based on fitting a straight line through the means for each amendment. Statistical analysis was conducted by developing the probability of a greater t of $RP_{(<0.45)}$ concentration in runoff water with 0, 4.5, 9, or 13.5 Mg ha^{-1} composted dairy manure additions as affected by chemical amendments compared with no amendment at 10-, 20-, 30-, and 40-min sampling times. Regression equations and the probability of a greater t were also developed for the measurement of $RP_{(<0.45)}$ concentration in the tank after drainage was complete. With this method, the impact of the amendments to reduce $RP_{(<0.45)}$ concentration as manure rate increased was evaluated.

In the second runoff event, statistical analysis was conducted by developing regression equations of $RP_{(<0.45)}$ concentration in runoff water vs. sampling time (10, 20, 30, and 40 min) for each of the 0, 4.5, 9, or 13.5 Mg ha^{-1} composted dairy manure additions. The probability of a greater t of $RP_{(<0.45)}$ in runoff water for 4.5, 9, or 13.5 Mg ha^{-1} composted dairy manure additions compared with no manure at 10-, 20-, 30-, and 40-min sampling times as affected by chemical amendments was developed. This statistical analysis evaluation examined the potential of the amendments to maintain any $RP_{(<0.45)}$ reduction over subsequent runoff events.

RESULTS AND DISCUSSION

Initial Dissolved Reactive Phosphorus [$RP_{(<0.45)}$] Reduction

The objective of the first part of the study was to evaluate how nutrient movement in concentrated water flow through the grass thatch layer could be impacted by the addition of chemical amendments. Means for $RP_{(<0.45)}$ concentrations as affected by manure application and the amendments are shown for each sampling time in Table 2. Regression equations developed for $RP_{(<0.45)}$ concentration vs. manure application rate are shown in Fig. 1. Very good relationships between the application of manure and the concentration of $RP_{(<0.45)}$ in the runoff were observed at the 10-min sampling time for all three of the chemical amendments and for no chemical amendment (Fig. 1). This was demonstrated by very high r^2 values observed for the regression equations at 10-min sampling time. Clearly, the increasing $RP_{(<0.45)}$ levels observed in the runoff as the rate of manure was increased indicated that the composted dairy manure was contributing $RP_{(<0.45)}$ to the runoff water.

The regression lines indicated that initially the ferrous sulfate was very effective and that the lime and the gypsum were somewhat effective at reducing the level of $RP_{(<0.45)}$ lost from the grass surface in the runoff water (Fig. 1). This was demonstrated in Table 3, which shows the probability of a greater t comparisons for each of the chemical amendments to be different than no chemical amendment. At the 10-min sampling time, no difference was seen at the 0 Mg ha^{-1} rate because no new P was added for the chemical amendment to have an effect of reducing the $RP_{(<0.45)}$ in runoff. However, at the highest rate of manure application (13.5 Mg ha^{-1}) a significant difference was observed with all three chemical amendments to reduce the concentration of $RP_{(<0.45)}$ in runoff compared with no chemical amendment. Since lime is a common agronomic input utilized to control soil pH and gypsum is used to add Ca or S to the soil, the application of lime or gypsum in conjunction with manure application could potentially reduce the initial level of $RP_{(<0.45)}$ that is contributed to the environment from short-duration runoff events.

Table 2. Means of dissolved molybdate reactive phosphorus filtered through a 0.45-μm membrane [$RP_{(<0.45)}$] in runoff water with 0, 4.5, 9, or 13.5 Mg ha^{-1} composted dairy manure additions as affected by chemical amendments compared with no soil amendment at 10-, 20-, 30-, and 40-min sampling times and for total runoff volume.

	Mean $RP_{(<0.45)}$			
	Composted dairy manure addition (Mg ha^{-1})			
Amendment	**0**	**4.5**	**9.0**	**13.5**
	mg L^{-1}			
		10-min sampling time		
None	0.225	0.442	0.768	1.128
$FeSO_4$	0.077	0.083	0.193	0.207
Gypsum	0.243	0.443	0.507	0.770
Lime	0.170	0.430	0.677	0.853
		20-min sampling time		
None	0.289	0.316	0.556	0.616
$FeSO_4$	0.067	0.113	0.127	0.127
Gypsum	0.153	0.317	0.383	0.607
Lime	0.137	0.323	0.533	0.740
		30-min sampling time		
None	0.232	0.312	0.472	0.469
$FeSO_4$	0.073	0.107	0.063	0.090
Gypsum	0.163	0.297	0.467	0.557
Lime	0.140	0.323	0.447	0.610
		40-min sampling time		
None	0.248	0.537	0.614	0.587
$FeSO_4$	0.073	0.083	0.190	0.130
Gypsum	0.226	0.317	0.677	0.873
Lime	0.283	0.453	0.486	0.640
		Tank		
None	0.368	0.469	0.696	0.682
$FeSO_4$	0.247	0.303	0.387	0.230
Gypsum	0.250	0.447	0.587	1.040
Lime	0.197	0.433	0.580	0.797

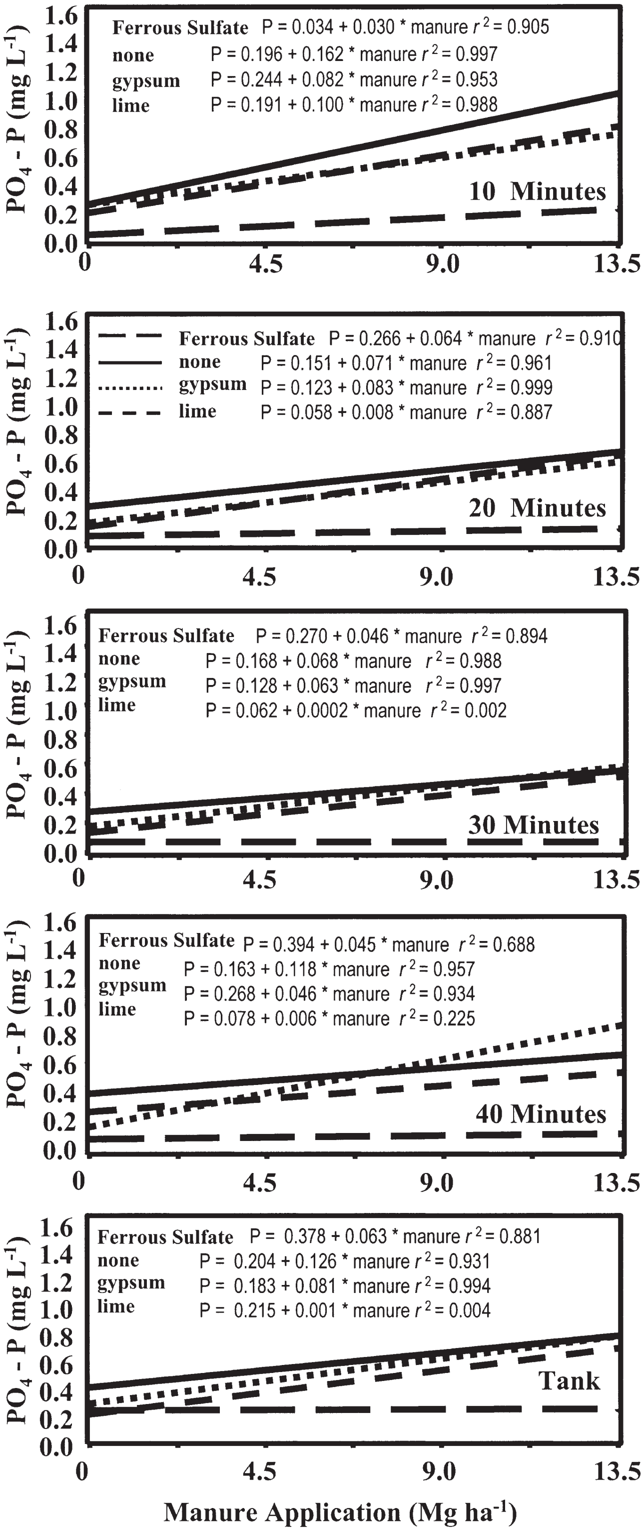

Fig. 1. Regression relationships of composted dairy manure application rate to concentration of dissolved molybdate reactive phosphorus filtered through a 0.45-μm membrane [$RP_{(<0.45)}$] in runoff as affected by chemical amendments gypsum, lime, and ferrous sulfate measured at 10-, 20-, 30-, and 40-min sampling times and in the tank after the runoff event.

Table 3. Probability of a greater *t* of dissolved molybdate reactive phosphorus filtered through a 0.45-μm membrane [$RP_{(<0.45)}$] in runoff water with 0, 4.5, 9, or 13.5 Mg ha^{-1} composted dairy manure additions as affected by chemical amendments compared with no soil amendment at 10-, 20-, 30-, and 40-min sampling times and for total runoff volume.

	$P > t$			
	Composted dairy manure addition (Mg ha^{-1})			
Amendment	0	4.5	9.0	13.5
		10-min sampling time		
$FeSO_4$	0.397	0.340	0.001	<0.001
Gypsum	0.916	0.991	0.116	0.034
Lime	0.753	0.944	0.576	0.099
		20-min sampling time		
$FeSO_4$	0.119	0.112	0.001	<0.001
Gypsum	0.338	0.997	0.175	0.940
Lime	0.283	0.955	0.856	0.329
		30-min sampling time		
$FeSO_4$	0.150	0.047	<0.001	<0.001
Gypsum	0.531	0.877	0.956	0.385
Lime	0.401	0.912	0.799	0.166
		40-min sampling time		
$FeSO_4$	0.405	0.004	0.007	0.004
Gypsum	0.920	0.145	0.673	0.060
Lime	0.867	0.576	0.443	0.723
		Tank		
$FeSO_4$	0.639	0.381	0.106	0.020
Gypsum	0.648	0.906	0.563	0.062
Lime	0.508	0.850	0.540	0.543

At the 20-min sampling time, a significant regression equation for $RP_{(<0.45)}$ vs. manure application was found for all three chemical amendments and no chemical amendment, with very good r^2 values observed for all of the regression lines (Fig. 1). Again, ferrous sulfate was very effective at reducing the concentration of $RP_{(<0.45)}$ in runoff, with a significant reduction in the $RP_{(<0.45)}$ compared with no chemical amendment observed at the 9 and 13.5 Mg ha^{-1} manure application rates (Table 3). However, the gypsum and lime were not effective at reducing the $RP_{(<0.45)}$ concentrations compared with no chemical amendments at this sampling time (Table 3). Similarly, at the 30- and 40-min sampling times, the regression lines indicated that ferrous sulfate was very effective at reducing $RP_{(<0.45)}$ concentration in runoff, while no difference was observed for the gypsum and lime (except for gypsum with 13.5 Mg ha^{-1} at 40 min) (Fig. 1; Tables 2 and 3). Anderson et al. (1995) reported that gypsum application to soils amended with dairy manure reduced $RP_{(<0.45)}$ from 40 to 60%, and Dao (1999) reported a 50 and 83% reduction in water-extractable P in composted feedlot manure from the addition of gypsum and caliche, respectively. However, it appears that under the conditions of concentrated water flow through grass thatch, the effectiveness of the lime and gypsum to reduce $RP_{(<0.45)}$ concentration in runoff was lost after about 10 min of runoff, while the effectiveness of the ferrous sulfate to reduce $RP_{(<0.45)}$ losses from the manure was steady over the duration of the runoff event. In fact, ferrous sulfate was so effective at intercepting $RP_{(<0.45)}$ during the latter part of the runoff event that only very poor regression equations for $RP_{(<0.45)}$ concentration vs. manure application could be developed.

This can be observed with the very low r^2 values observed with ferrous sulfate at the 30- and 40-min sampling times ($r^2 = 0.002$ and 0.225, respectively, Fig. 1) and a very flat slope.

Careful examination of the regression graphs indicates a reduction in the level of $RP_{(<0.45)}$ contribution from the manure application as the runoff event progressed. For example, at the 10-min sampling time, $RP_{(<0.45)}$ concentration in runoff measured for the 13.6 Mg ha^{-1} manure application level was 1.13 mg L^{-1}, compared with 0.59 mg L^{-1} at the 40-min sampling time (Fig. 1). The data indicate that the gypsum and lime did have an initial impact for reducing the $RP_{(<0.45)}$ concentration when the contribution of $RP_{(<0.45)}$ to the environment was at its highest. This indicates that lime and gypsum could be used to reduce the initial impact of the manure application. The most appropriate use of lime and gypsum to control $RP_{(<0.45)}$ losses from manure may be in areas of fields where saturated zones (Dougherty et al., 2004) are infrequent and water runoff events are occasional and the amount of concentrated runoff water is expected to be small. Also, the rate of Ca added in this experiment was relatively low compared with the rates used for pH control and Ca fertility additions, and even the Ca that would be added with the addition of the compost itself. The gypsum and lime additions may be more effective if added at higher rates.

Water samples were collected from the tank receiving the runoff from the grass surface (Table 2; Fig. 1). The tank measured the cumulative effect of the $RP_{(<0.45)}$ losses over the duration of the runoff event and therefore integrates the changing interaction of the manure application to the $RP_{(<0.45)}$ concentration in runoff. Regression lines were developed for the concentration of $RP_{(<0.45)}$ in the tank vs. the manure application (Fig. 1). As was observed with the discrete sampling at specified times, good relationships could be developed for the $RP_{(<0.45)}$ concentration relative to the manure application rate for the gypsum and lime chemical amendments as well as for no chemical amendment as denoted by the high r^2 values observed (Fig. 1).

The regression line developed for the tank measurements for ferrous sulfate was very poor, with a r^2 value of only 0.004 (Fig. 1) and a very flat slope, denoting that there was no real relationship between the concentration of $RP_{(<0.45)}$ and the application of manure when ferrous sulfate was added to the grass surface. Apparently, the ferrous sulfate was so effective at reducing the $RP_{(<0.45)}$ as the water ran through the grass thatch that it was undistinguishable from no manure application.

Studies have shown that amendments mixed with manure could reduce the potential P losses (Moore and Miller, 1994; Anderson et al., 1995; Dao, 1999; Dao et al., 2001; Dou et al., 2003), but this study separates the effect of the amendments from the manure so that the potential for reduction could be evaluated as a separate operation and with concentrated runoff flow through the thatch layer. The results of this study indicate that ferrous sulfate has a considerable potential to be used in conjunction with manure application on grassed and filter strips to reduce the initial $RP_{(<0.45)}$ losses to the environment.

Long-Term Dissolved Reactive Phosphorus [$RP_{(<0.45)}$] Reduction

The second part of the study was to evaluate whether the chemical amendments could potentially extend the impact of reducing $RP_{(<0.45)}$ contribution in runoff (Table 4). To accomplish this, a second runoff event was initiated 24 h later in the same run-over boxes. In this portion of the study, the probability of a greater t was developed for the $RP_{(<0.45)}$ in runoff water for each of the manure application rates compared with no manure at 10-, 20-, 30-, and 40-min sampling times as affected by chemical amendments. This was to examine whether the potential benefits of chemical amendments would persist. In this effort, we wanted to examine the grass surfaces previously impacted by runoff. While this method cannot predict the long-term impacts of chemical additions to the manure on $RP_{(<0.45)}$ loss, it was useful in examining potential conditions that could develop after manure application.

The results show that the slope of the regression lines was very flat, with little or no change in the amount of $RP_{(<0.45)}$ measured over the duration of the runoff event for all three chemical amendments (Table 4, Fig. 2). This indicated that the manure-enriched sod environment had reached a steady condition. Results for gypsum and lime indicated that the concentration of $RP_{(<0.45)}$ in runoff increased with increased manure application rate, with the higher rates of manure contributing a low but continuous level of $RP_{(<0.45)}$ to the runoff water. However, with ferrous sulfate, no significant difference could be observed between the application of 13.5 Mg ha^{-1} manure and no manure (Table 4, Fig. 2). This was statistically demonstrated in Table 5, where a significant difference indicated an increase in the contribution of

Table 4. Means of dissolved molybdate reactive phosphorus filtered through a 0.45-μm membrane [$RP_{(<0.45)}$] in runoff water for the second runoff event for 4.5, 9, or 13.5 Mg ha^{-1} composted dairy manure additions compared with no manure additions at 10-, 20-, 30-, and 40-min sampling times as affected by chemical amendments over an extended time.

	Mean $RP_{(<0.45)}$			
	Sampling time (min)			
Manure	10	20	30	40
Mg ha^{-1}	mg L^{-1}			
	$FeSO_4$			
0	0.097	0.023	0.023	0.070
4.5	0.080	0.057	0.067	0.063
9.0	0.133	0.053	0.050	0.000
13.5	0.123	0.073	0.033	0.073
	Gypsum			
0	0.198	0.200	0.193	0.217
4.5	0.307	0.277	0.190	0.377
9.0	0.440	0.383	0.280	0.463
13.5	0.443	0.400	0.383	0.477
	Lime			
0	0.130	0.1233	0.080	0.140
4.5	0.207	0.190	0.133	0.253
9.0	0.360	0.283	0.293	0.250
13.5	0.380	0.553	0.330	0.400

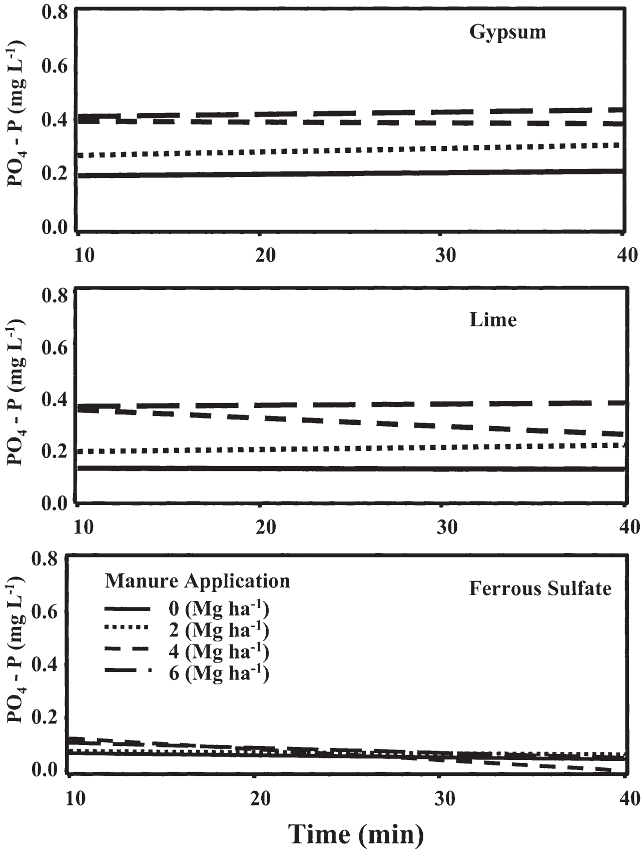

Fig. 2. Regression relationships of the concentration of dissolved molybdate reactive phosphorus filtered through a 0.45-μm membrane [$RP_{(<0.45)}$] in runoff for the second runoff event over sampling time as affected by composted dairy manure rate for the chemical amendments gypsum, lime, and ferrous sulfate.

$RP_{(<0.45)}$ when manure was compared with no manure. In this case, significant differences were not observed at the lowest manure application rate (4.5 Mg ha^{-1}). However, with the gypsum and lime, significant differences were observed at both the 9 and 13.5 mg ha^{-1} manure application rates at most of the sampling times (Table 5). With the ferrous sulfate, no significant difference was observed for the concentration of $RP_{(<0.45)}$ in runoff at any manure application rates at any sampling times (Table 5). This indicated that not only was the ferrous sulfate effective at reducing $RP_{(<0.45)}$ for an extended period of time compared with the no amendment treatment, it did so at all manure rates and did a better job than lime and gypsum.

Table 5. Probability of a greater *t* in the second runoff event of dissolved molybdate reactive phosphorus filtered through a 0.45-μm membrane [$RP_{(<0.45)}$] in runoff water for 4.5, 9, or 13.5 Mg ha^{-1} composted dairy manure additions compared with no manure additions at 10-, 20-, 30-, and 40-min sampling times as affected by chemical amendments over an extended time.

	$P > t$			
	Sampling time (min)			
Manure	10	20	30	40
Mg ha^{-1}				
		$FeSO_4$		
4.5	0.895	0.790	0.606	0.962
9.0	0.771	0.811	0.751	0.615
13.5	0.833	0.690	0.905	0.981
		Gypsum		
4.5	0.453	0.541	0.968	0.253
9.0	0.099	0.147	0.305	0.082
13.5	0.094	0.114	0.028	0.067
		Lime		
4.5	0.544	0.595	0.526	0.416
9.0	0.074	0.205	0.014	0.430
13.5	0.053	0.001	0.005	0.067

Due to the reduction in $RP_{(<0.45)}$ losses with ferrous sulfate during the first runoff event, there would be more P remaining on and in the turf compared with the other treatments. Potentially, the ferrous sulfate treatment could have been expected to contribute more $RP_{(<0.45)}$ to the runoff water because a smaller portion of the manure P had been released in the previous runoff event compared with the other amendments. Instead, after an additional 40 min of runoff water had run through the grass sod interacting with the applied manure, no significant difference could be observed compared with no manure (Table 5). This is a clear indication that the addition of ferrous sulfate in conjunction with manure application could potentially be used to reduce the levels of $RP_{(<0.45)}$ that are lost to the environment. Also, as long as soil erosion is controlled and the P remained complexed over time, most of the P would likely remain in place. Further, because the ferrous sulfate and the manure were not mixed before application, this could potentially demonstrate that the ferrous sulfate could be used in grassed areas at the edge of fields (e.g., such as filter strips) to intercept the movement of $RP_{(<0.45)}$ off fields and potentially reduce the level of $RP_{(<0.45)}$ that reaches downstream water bodies. Further research is needed to verify the $RP_{(<0.45)}$ reduction with ferrous sulfate additions under field conditions, and to determine the optimum rate of ferrous sulfate to effectively reduce $RP_{(<0.45)}$ concentrations in runoff.

CONCLUSIONS

Regression equations show a very good relationship between the application of composted dairy manure and the concentration of $RP_{(<0.45)}$ in runoff. The results indicated that after 10 min of runoff, ferrous sulfate was very effective at reducing the level of $RP_{(<0.45)}$ that was lost from the grass surface in the runoff water and that lime and gypsum were somewhat effective. This indicated that the addition of lime to control soil pH or the use of gypsum to add Ca or S to the soil could be used in conjunction with manure application to potentially reduce the contribution of $RP_{(<0.45)}$ to the environment from the manure. After 20 min, ferrous sulfate was still very effective at reducing the concentration of $RP_{(<0.45)}$ in runoff, but gypsum and lime no longer had a significant effect. The data indicate lime and gypsum could possibly be used to reduce the initial impact of the manure application, but would need to be used in areas with infrequent and low volume runoff events.

The addition of ferrous sulfate to the sod surface was so effective at reducing the $RP_{(<0.45)}$ that it was undistinguishable from no manure application. Further, in subsequent runoff events, no difference was observed from the treatments receiving 13.5 Mg ha^{-1} of manure and those receiving no manure when ferrous sulfate was added. This indicates that ferrous sulfate has a considerable potential to be used in conjunction with manure application on pasture, turfgrass, and filter strips to reduce the initial $RP_{(<0.45)}$ losses to the environment.

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