PHOSPHORUS RUNOFF POTENTIAL
OF SELECTED BENCHMARK
SOILS IN OKLAHOMA

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Chapter 1

EFFECTS OF SOIL TYPE AND PHOSPHORUS LEVEL ON PHOSPHORUS LOSS IN RUNOFF

ABSTRACT

The loss of phosphorus (P) in runoff from agricultural soils may accelerate eutrophication in lakes and streams and degrade surface water quality. Several management strategies are being developed to minimize agricultural runoff P by considering P loss risk factors, such as, soil P level and transport mechanism. Current standards of soil P levels for manure application are often based upon professional judgment rather than scientific data, as limited soil specific data exist on the relationship between runoff P and soil P. This study investigates the relationship between runoff P and soil P for three Oklahoma benchmark soils: Richfield, Dennis, and Kirkland series. Surface soil (0-15 cm) was collected from three designated locations across Oklahoma, treated with diammonium phosphate (18-46-0) to establish a wide range of Mehlich 3 P level (25-1016 mg kg^{-1}), and allowed to reach a steady state (210 days) in 1m x 0.42m boxes before rainfall simulation. The rainfall simulation was conducted at an intensity of 75 mm hr^{-1} on 5% sloped soil boxes. Measurable runoff was collected for 30 min. and analyzed for dissolved reactive P and total P. Soil samples collected immediately prior to rainfall simulation were analyzed for the following soil P values: Mehlich 3 P, water soluble P, ammonium oxalate P saturation index, and

P saturation based on sorption maximum. Runoff dissolved reactive P concentration was significantly ($p<0.05$) correlated to M3P ($r^2=0.92$-0.95), WSP ($r^2=0.88$-0.96), $\mathrm{PSI}_{\mathrm{OX}}$ ($r^2=0.84$-0.94), and $\mathrm{PSI}_{\mathrm{Smax}}$ ($r^2=0.89$-0.96). However, the relationship between runoff dissolved reactive P and soil P varied between soils, indicating that P loss to surface water would also vary by soil. Low dissolved reactive P concentrations coincided with low runoff volumes suggesting soil hydrology has an impact on the relationship between runoff P and soil test P.

INTRODUCTION

Eutrophication of many streams and lakes has been accelerated due to the influx of phosphorus (P) from agricultural surface runoff (Pote et al., 1999). According to USEPA (1998), agriculture has been identified as the primary source of non-point source (NPS) pollution degrading the quality of stream and lake water. Especially the transport of P from agricultural soils has been recognized as an important contributor to the degradation of surface water quality (Sims et al., 1998; USEPA, 1998). As a result, a considerable amount of research has been conducted to provide knowledge of P transport processes from soil as a P source to surface water.

A better understanding of P transport process will provide more accurate information to develop site specific P management strategies. The P risk index is a tool to assess various landforms and management practices for potential risk of P movement to water bodies that considers P source and transport factors (Lemunyon and Gilbert, 1993). Many states (e.g. Oklahoma) are currently in the process of developing state specific P risk indices. Generally, the factors contributing to P loss potential are weighted and a relative risk index is derived from the sum of the weighted factors. However, the weights and the relative P loss index have been derived primarily from professional judgment, as there is limited site-specific data (Lemunyon and Gilbert, 1993).

Many researchers have found that the P content of the surface soil directly influences the loss of P in runoff (Romkens and Nelson, 1974; Daniel et al., 1994). Other researchers have shown significant relationships between soil P and runoff P concentration (Wendt and Alberts, 1983; Sharpley, 1995; Pote et al., 1999; Cox and Hendricks, 2000). Because there exists a relationship between runoff P and soil test P, there should be a critical level of soil P that could result in runoff P concentrations high enough to impact water quality (Daniel et al., 1994). An effective management strategy to minimize P loss in runoff is to identify this critical level in soil and to prevent further P addition to that soil. It is the goal of many states and federal water quality agencies to identify critical levels for benchmark soils and establish cut-off limits for additional P application (Daniel et al., 1994). However, the critical levels and the relationships between runoff P and soil P are soil specific and dependent upon soil and site characteristics (Daniel et al., 1994; Sharpley, 1995; Pote et al., 1999; Cox and Hendricks, 2000).

In a review paper, Sharpley (1996) compared the findings from eight studies and found that the relationship between runoff dissolved reactive P (DRP) and Bray 1 P varied markedly among soils tested, indicating that soil type influences the relationship between runoff P and soil P. Cox and Hendricks (2000) found that two soils with clay contents of 5% and 32% would require soil Mehlich 3 P (M3P) values of 253 mg dm^{-3} and over 700 mg dm^{-3}, respectively to produce runoff DRP concentrations of 1 mg L^{-1}. Using ammonium oxalate extractable Fe, Al, and P, Hooda et al. (2000) found that ammonium oxalate P saturation index (PSI_{OX}) was the most significant soil property for predicting water desorbable P from contrasting soils. Therefore, runoff P – soil P relationships used to assess the potential for P loss in runoff will probably have to be soil and site specific (Sharpley, 1995).

As many researchers have illustrated the relationship between runoff P and soil P among a wide range of soil types, few have compared multiple soils within one study. Using ten Oklahoma soils, Sharpley (1995) illustrated soil specific relationships between runoff P and M3P. However, by correlating DRP with soil P sorption maxima (S_{max}), it was found that a single relationship could be used to describe all ten soils. This study suggests that soil P saturation based on sorption maxima determines the potential for P loss in runoff (Sharpley, 1995).

Using three Ultisols, Pote et al. (1999) also found soil specific relationships between runoff DRP and soil water soluble P (WSP). However, it was found that the differences between the three soils evaluated could be corrected by normalizing the DRP to runoff depth (cm). This finding suggests that the relationship between runoff P and soil P is dependent upon soil hydrology.

As both the physical and chemical properties of soil have been proven to profoundly affect the relationship between runoff P and soil P it is important to differentiate, if possible, which property may be the most important. Such data are essential to the development of a P risk index to be used as a site specific risk assessment and management tool. The objectives of this study are: (i) to evaluate the impact of soil P on runoff P in three soil series within the Mollisol order and (ii) to study how soil physical and chemical properties influence runoff P.

METHODS AND MATERIALS

Soil

Three Oklahoma benchmark soils, Richfield, Dennis and Kirkland, were selected for this study on the basis of geographic location, major land use area, and physical properties (USDA – NRCS, 2000). The three soils were collected from agricultural research stations located across Oklahoma (Fig. 1.1).

At each of the three locations, the top 15 cm of soil was collected using a front-end loader. After collection, the soils were sieved (16 mm screen) to remove rocks and plant materials, and then homogenized using an industrial mortar mixer. Four diammonium phosphate (DAP) fertilizer treatments were applied to each soil to reach predetermined M3P levels (Table 1.2). Dissolved DAP fertilizer treatments were applied using a pressure sprayer during soil homogenization. Fertilizer was added using an estimate of adding 2 mg fertilizer P per kg of soil to raise soil M3P by 1 mg kg $^{-1}$ (Philip Moore, personal communication). The treated and mixed soils were placed in 42.25cm W x 100cm L x 13.75cm H wooden, mesh-bottomed boxes to a depth of 13 cm (Fig. 1.2). There were 48 boxes in total (3 soils, 4 treatments/soil test P levels, and 4 replications). The soils were frequently irrigated and allowed to reach a steady state for M3P over a period of 210 days before rainfall simulation took place. Representative soil samples were taken periodically to monitor M3P changes over time. Plants were not grown in the soil boxes throughout the experiment.

Rainfall Simulation

The rainfall simulation was conducted using a solenoid-operated, variable intensity rainfall simulator based on the design of Miller (1987) (Fig. 1.2) over the week of June 25, 2001. The simulator has one TeeJet™ ½ HH-SS50WSQ nozzle placed in the center of the 3m H x 2.8m L x 2.3m W aluminum frame. The intensity of the simulated rainfall was controlled by the on-off spraying times (1.3 s on, 0.4 s off) of the nozzle. The pressure of the water supply for the rainfall simulator was calibrated to deliver 75 mm hr $^{-1}$, which is in accordance with the protocol recommended by the National Phosphorus Research Project (2002) and equivalent to a 10-year storm event in north-central Oklahoma (USDC, 1961).

Twenty-four hr. prior to the rainfall simulation, the boxes were irrigated until saturation and the excess water drained naturally. The bare soil surfaces were roughed to a depth of 3cm to simulate a freshly tilled field. All runoff water from each box was guided over a metal collection plate to one collection outlet connected to a 16 mm rubber garden hose that dumped into a 17 L collection container sealed with a watertight lid. Paraffin wax was used as a sealant between the soil surface and the metal runoff collection plate to prevent any runoff leakage from occurring during the rainfall simulation. Rainfall was applied to soil boxes on a 5% slope until 30 min. of measurable runoff was collected. From each collection container, total runoff volume was recorded for each soil box. Collected runoff was manually agitated to re-suspend sediment before one representative runoff sample (500 ml) was obtained for analyses. In addition, an aliquot (500 ml) of well-mixed runoff from the B treatment for all soils and replications was collected every 5 min. throughout the 30 min. runoff duration to evaluate changes in runoff volume and P concentration over time. Soil samples were collected from each box prior to rainfall simulation, and analyzed for different forms of P and then correlated with runoff P.

Soil and Runoff Analyses

Mehlich 3 extractable P (M3P, Mehlich, 1984), water soluble P (WSP, Self-Davis et al., 2000), P sorption maxima, ammonium oxalate extractable P, Al and Fe, texture, soil organic matter (SOM), and pH was determined for the three soils series evaluated. Soil characterization results are summarized in Table 1.1. Phosphorus sorption isotherms were constructed by shaking (end-over-end, 24 hr.) 1 g soil with 25 ml of the following concentrations of P in 0.01 M $CaCl_2$ solution: 0, 0.5, 1, 5, 10, 15, 20, 25, 40, and 50 mg/L (Graetz and Nair, 2000). The samples were centrifuged at 10,000 rpm (14,470 x g) for 5 min., filtered (0.45 μm), and analyzed colorimetrically (Murphy and Riley, 1962). Phosphorus sorption maximum (Smax) was determined as 1/slope of the linear Langmuir equation for each soil (Graetz and Nair, 2000).

Mehlich 3 P was extracted by shaking (end-over-end, 5 min.) 2 g of soil with 20 ml of Mehlich 3 extractant (Mehlich, 1984). The extracts were filtered (Whatman #4) and analyzed colorimetrically (Murphy and Riley, 1962). In addition, P sorption saturation (PSI_{Smax}) was computed using soil WSP (mg kg^{-1}) and S_{max} (mg kg^{-1}) by the following equation (Sharpley, 1995):

$$PSI_{Smax}\,(\%) = (WSP/\ Smax)*100 \qquad [eq.\ 1]$$

Soil WSP was extracted by shaking 2 g of soil (end-over-end, 1 hr.) with 20 ml of distilled water and centrifuging at 10,000 rpm (14,470 x g) for 5 min.

(Self-Davis et al., 2000). The supernatant was filtered (0.45 µm) and analyzed for P colorimetrically (Murphy and Riley, 1962).

Ammonium oxalate extractable P, Al, and Fe was also measured. Thirty ml of ammonium oxalate solution (16.2 g ammonium oxalate monohydrate, 10.8 g oxalic acid dihydrate made to one L with deionized water) (Schoumans, 2000) was shaken (end-over-end, 2 hr) with 1.5 g of soil, filtered (Whatman #4), and analyzed for Fe, Al, and P using an ICP-AES. Phosphorus saturation index by ammonium oxalate extraction (PSI_{OX}) was computed using the P, Al, and Fe contents (mmol kg^{-1}) using the following equation (Schoumans, 2000):

$$PSI_{OX}\ (\%) = ([P]/\ [Fe + Al])*100 \qquad [eq.\ 2]$$

Soil texture was determined using the hydrometer method (Klute, 1986). Soil pH was determined using a glass electrode at a 1:1 soil/water ratio (w/v). Soil organic matter was determined using a modified loss-on-ignition method described by Ben-Dor and Banin (1989) in which 2 g of soil was placed in a 150°C oven to remove moisture (2 hr.), weighed (W1) then placed in a 425°C oven to remove organic matter (2 hr.) and weighed again (W2). Soil organic matter was calculated using the following equation:

$$SOM\ (\%) = [(W1 - W2)/\ W2]*100 \qquad [eq.\ 3]$$

Immediately after rainfall simulation, an aliquot of runoff water sample was filtered (0.45µm) and analyzed colorimetrically (Murphy and Riley, 1962) to determine dissolved reactive P (DRP, Pote and Daniel, 2000). Total P (TP) from each runoff sample was determined by digesting 25 ml of runoff at 175°C with 1 ml concentrated H_2SO_4 and 5 ml concentrated HNO_3 until a total volume of 1 ml remained (Pote and Daniel, 2000). All digested samples were neutralized and analyzed for P colorimetrically (Murphy and Riley, 1962). Particulate P (PP) was calculated by subtracting DRP from TP. Runoff TP and DRP loads (mg) were computed by multiplying DRP and TP concentration (mg L^{-1}) by total runoff volume (L).

Total suspended solids (TSS) were determined for all runoff water samples by vacuum filtering (0.45µm) 50 ml of well-mixed runoff water sample and drying the vacuum filter cup and filter paper at 95°C. The initial dry weight of the vacuum cup and filter was subtracted from the final dry weight of the sediment, vacuum cup and filter to give TSS. Runoff TSS load (mg) was calculated by multiplying TSS (mg L^{-1}) by runoff volume (L) for all runoff water samples.

Statistical Analysis

Simple linear regression was used to correlate runoff DRP and TP concentrations with different soil P for all plots. The strengths of these correlations were expressed by the coefficient of determination (r^2 value). These data were also analyzed for significant differences among the three soil series evaluated using analysis of covariance.

RESULTS AND DISCUSSION

The Effect of Fertilizer P on Soil Test P

Soil samples were collected from all soil treatments and analyzed periodically over a year to assess the effect of fertilizer P on soil test P (STP) over time. After fertilizer application, soil M3P increased sharply as the amount of fertilizer P increased (Table 1.2). However, soil M3P decreased with time since the first sampling. All three soil series evaluated followed a pattern of rapidly decreasing M3P through the first 60 days followed by a slower decrease through 120 days. During the remainder of the experiment, M3P continued to decrease slowly and reached a steady state by 210 days (Fig. 1.3). This suggests that a considerable amount of free P exists either in solution or as undissolved P fertilizer shortly after P fertilizer application. This free P is easily extractable and susceptible to dissolution and transport during a runoff event resulting in greater P runoff risk. With time this free P is gradually precipitated as Fe and Al phosphates in low pH soils or as Ca phosphates in higher pH soils. Ultimately, apatite compounds may form over great periods of time rendering soil P relatively insoluble (Pierzynski et al., 1994; Havlin et al., 1999). As runoff P is directly related to soil test P, the length of time between P application and the first runoff event is very important (Sharpley et al., 1994; Daniel et al., 1994). This suggests that as soil P was highest shortly after P fertilizer application, runoff P would also be highest immediately after fertilizer application.

Based on the changes of M3P averaged over all three soils 1 yr. after P fertilizer addition, it was determined that soil M3P would be raised 1 mg kg^{-1} by the addition of 1.48 mg kg^{-1} fertilizer P or a fertilizer P to M3P ratio of 1.48:1 (Fig 1.4). More specifically, the Richfield and Dennis series had very similar results requiring ratios of 1.56:1 and 1.58:1, respectively, and the Kirkland series required 1.32:1. From a long term soil fertility field study, Johnson et al. (1998) found that the addition of as much as 6 mg kg^{-1} fertilizer P is required to raise soil M3P 1 mg kg^{-1}. It is difficult to compare the results of this study with the field data since the field study lasted for more than 25 yrs. and field P loss beyond crop removal was not included. However, the present study collected data in a controlled environment over a period of one year. Producers and researchers would be able to predict STP if the relationship between STP and P addition can be established, but short-term experiments may result in different relationships from those derived from long term field data.

Impact of Runoff Duration on Runoff P

Simulated rainfall was applied to all soil boxes at an intensity of 75 mm hr^{-1}. At this intensity, measurable runoff began 4 to 7 min. after rainfall was applied to soil boxes. Rainwater penetrated through the soil surface or accumulated in small depressions before runoff started. Infiltration rates were determined by subtracting the volume of runoff collected in 5 min. intervals from the total volume of rainfall that was applied to the soil surface during the same time period. Overall infiltration rates were greatest for the Dennis series (Fig. 1.5). Consequently, the Dennis series resulted in lowest runoff volumes while the Kirkland and Richfield series had higher but similar runoff volumes and infiltration rates (Fig 1.5).

Runoff water samples were also taken from the 235, 225, and 180 mg kg^{-1} treatments (all replications) for the Richfield, Dennis, and Kirkland soil, respectively, every 5 min. to evaluate runoff P changes over the observed 30 min. runoff duration. The DRP concentration of the 5 min. samples decreased with time over the 30 min. runoff duration and was negatively correlated (r^2=0.64-0.97; $p<0.05$) with runoff volume measured also at 5 min. intervals (Fig 1.6, 1.7). Total P (TP) in the runoff of 5 min. samples also decreased with time and was negatively correlated to runoff volume as increasing runoff volume with time diluted the runoff TP concentration. These data suggest that over longer rainfall – runoff duration runoff P concentrations would likely continue to decrease. This is in agreement with Quinton et al. (2001) who found that runoff P concentrations generally decreased with increasing rainfall - runoff event duration.

Relationships between Runoff P and Soil P

Soil samples were collected immediately prior to rainfall simulation and analyzed for M3P, WSP, PSI_{OX} and PSI_{Smax} (Table 1.2). All these soil P values were well correlated among themselves and were used to correlate with runoff properties. In addition, the source water (potable well water) used for the rainfall simulation had an average TP and DRP of 0.07 mg L^{-1}.

Total P concentrations in runoff ranged from 1.0 to 13.8 mg L^{-1} for all treatments (Table 1.3). Total P was significantly ($p<0.05$) correlated to M3P (r^2=0.81-0.92), WSP (r^2=0.77-0.85), PSI_{OX} (r^2=0.66-0.85), and PSI_{Smax} (r^2=0.81-0.92). However, particulate P (PP) was not well correlated to soil M3P, WSP,

PSI_{OX}, or PSI_{Smax}. Particulate P constituted most (>58%) of TP for all treatments although the percentage of PP decreased with an increase in soil P (Table 1.3).

Runoff DRP ranged from 0.1 to 3.8 mg L^{-1} for all treatments (Table 1.3) and was significantly ($p<0.05$) correlated to M3P (r^2=0.92-0.95), WSP (r^2=0.88-0.96), PSI_{OX} (r^2=0.84-0.94), and PSI_{Smax} (r^2=0.92-0.95) (Table 1.4). Additionally, each soil series expressed a significantly ($p<0.05$) different relationship between DRP and soil WSP and M3P when compared among the three soil series. These findings are consistent with that found by Pote et al. (1999) among three Ultisols and other researchers who have studied the relationship between runoff P and soil P (Sharpley, 1995; Cox and Hendricks, 2000).

Although researchers have found that runoff P is often a function of P sorption capacities and texture (Cox and Hendricks, 2000; Sharpley 1995), the high levels of soil P in this study likely masked the influence of P sorption and texture on runoff P. As a result, the differences observed among the three soils in the runoff DRP-soil P relationship are probably a result of the varying hydrologic properties of the three soils evaluated in this study (Table 1.1). For example, the Dennis series, the soil with the lowest clay content and Smax, had the lowest DRP concentration at any given level of soil P. The Dennis series also displayed the greatest infiltration rate and consequently the smallest average runoff volume. Because the Dennis soil has a high infiltration rate relative to the remaining soils, the rain that strikes the soil surface is subject to greater infiltration and less surface flow and thus has a diminished ability to dissolve P and detach finer soil particles for transport in runoff. In addition, the

Dennis series resulted in the lowest overall TSS concentration, TP concentration, TP load, and DRP load.

The other two soils were similar in infiltration rate, though the Kirkland series produced a larger average runoff volume. The Kirkland series produced a lower concentration of DRP at high levels of soil P compared to the Richfield series. The Kirkland series also produced the largest concentration of TSS, TP and TP load. However, the Richfield series released the largest concentration of DRP and DRP load. The difference between the two being that PP constituted a larger portion of TP in the Kirkland series. This suggests that the Kirkland series is more susceptible to erosion processes than the Richfield series and the Richfield series has a higher potential to release DRP to runoff than the Kirkland series.

Several approaches were examined here in an effort to develop one regression equation to describe the relationship between runoff DRP and soil P for all three soils series. Each of these approaches considered a soil chemical or physical property to attempt to describe the relationship between runoff DRP and soil P for all three soils in one regression equation. The first approach was to normalize runoff DRP concentrations (mg L^{-1}) by including hydrologic data (runoff depth, mm) using the following equation:

$$\text{NDRP} = \text{DRP} / \text{Runoff depth} \qquad \text{[eq. 4]}$$

However, it was found that when normalized DRP (NDRP) was correlated to soil WSP the relationships remained soil-specific. This suggests one regression equation could not be used to accurately describe the relationship between runoff NDRP and soil P (Fig 1.12).

In a similar study, Pote et al. (1999) normalized runoff DRP concentrations in a similar manner for three Ultisols to correct for observed DRP-soil P relationship differences among soils. However, Pote et al. (1999) found that by normalizing runoff DRP concentration one regression equation could be used to describe the relationship between runoff DRP and soil P. As the Pote et al. (1999) study was performed on three Ultisols in a field situation, the hydrological properties of the soils evaluated were probably not impacted to the extent of the soils in this study. The soils in this study were removed from the field and sieved. Both of these actions may have impacted the physical properties (e.g. bulk density, pore volume, etc.) of the soils. In addition, this study worked with a much wider range of M3P and WSP and the differences between the regression lines seem to be amplified at high levels of M3P and WSP. Lastly, all soil surfaces in this study had no surface cover while the sites evaluated by Pote et al. (1999) were under well established tall fescue (*Festuca arundinacea*).

Another approach evaluated to correct for observed differences in the runoff DRP – soil P relationship considered the degree of soil P saturation. Runoff DRP was correlated to soil P sorption saturation index (PSI_{Smax}), which was calculated using soil WSP and soil P sorption maxima, and ammonium oxalate P sorption index (PSI_{OX}). For all three soils, runoff DRP was highly correlated (r^2=0.92-0.95; $p<0.05$) with PSI_{Smax}, although, the regression equations varied by soil (Table 1.4; Fig. 1.10). This suggests that one regression equation can't be used to describe the relationship between runoff DRP and soil PSI_{Smax}. However, Sharpley (1995) found that by relating runoff DRP to soil PSI_{Smax} (soil M3P/ Smax), one regression equation could be used to describe the dependence of runoff DRP on PSI_{Smax} from 10 soils recently amended with poultry litter.

Runoff DRP was also highly correlated (r^2=0.84-0.94; $p<0.05$) with PSI_{OX} (eq. 2) for all soils evaluated (Table 1.4; Fig. 1.11). By using the PSI_{OX} approach, it was found that one regression equation could be used to describe the DRP–PSI_{OX} relationship for both the Richfield and Kirkland soil series, but not for the Dennis series. Using PSI_{OX} shows promise as a soil analysis that may be used to describe the relationship between runoff DRP and soil P for groups of soils. However, further research is required to define the criteria needed to group soils to allow for general runoff DRP predictions based only upon PSI_{OX}. Furthermore, as PSI_{OX} is not a common soil analysis, additional expenses are needed to perform this test.

CONCLUSIONS

The addition of fertilizer P to the three soils in this experiment caused a dramatic increase in soil M3P initially. However, soil M3P decreased rapidly within the first 60 days and continued to change slowly through 120 days. By 210 days after P fertilizer addition, the change in soil M3P seemingly leveled off indicating that STP had reached a steady state. This information may be useful for timing experiments involving the addition of fertilizer P to soil environments, such as rainfall simulation experiments or to raise soil test P for other studies.

It was found the addition of about 1.5 mg fertilizer P for each kg soil raised M3P one unit (mg kg^{-1}) one year after P addition. As this was an indoor experiment, many environmental variables were controlled and thus provided an accurate assessment of the actual amount of fertilizer P required to raise soil M3P by one unit. This information may also provide useful for future controlled environment experiments involving the addition of fertilizer P to achieve a predetermined soil M3P level, and to estimate time required to reach a critical M3P level for farmers.

Dissolved reactive P and TP concentrations decreased over time during the 30 min. runoff duration for all soils tested. This suggests that with increased runoff duration, runoff P concentrations would likely continue to decrease.

Of the three soil series studied, runoff DRP and TP were highly correlated with soil M3P, WSP, PSI_{Smax}, and PSI_{OX}. However, the relationship between runoff DRP and soil M3P and soil WSP was significantly different for each soil series evaluated. Although relating runoff DRP to PSI_{Smax} and PSI_{OX} did not result in one regression equation that could describe the relationship between runoff DRP and soil P for all three soil series evaluated, using PSI_{OX} showed promise as a soil analysis that may be used to describe the relationship between runoff DRP and soil P for groups of soils. However, further research is required to define the soil property criteria needed to group soils to allow for general runoff DRP predictions based only upon PSI_{OX}.

In this study, soil hydrology seemed to be the most important soil property controlling runoff P concentrations. Low DRP concentrations coincided with low runoff volumes suggesting soil hydrology has an impact on the relationship between runoff P and soil test P.

REFERENCES

Ben-Dor, E., and A. Banin. 1989. Determination of organic matter content in arid-zone soils using a simple "loss-on-ignition" method. Commun. Soil Sci. Plant Anal. 20:1675-1695.

Cox, F.R., and S.E. Hendricks. 2000. Soil test phosphorus and clay content effects on runoff water quality. J. Environ. Qual. 29:1582-1586.

Daniel, T.C., A.N. Sharpley, D.R. Edwards, R. Wedepohl, and J.L. Lemunyon. 1994. Minimizing surface water eutrophication from agriculture by phosphorous management. J. Soil Water Conserv. 49:30-35.

Graetz, D.A., and V.D. Nair. 2000. Phosphorus sorption isotherm determination. p. 35-38. *In* G.M. Pierzynski (ed.) Methods for P analysis. Southern Cooperative Series Bulletin No. #396.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 1999. Soil fertility and fertilizers, 6th ed. Prentice-Hall, New Jersey

Hooda, P.S., A.R. Rendell, A.C. Edwards, P.J.A. Withers, M.N. Aitken, and V.W. Truesdale. 2000. Relating soil phosphorus indices to potential phosphorus release to water. J. Environ. Qual. 29:1166-1171.

Johnson, G.V., N.T. Basta, H.A. Zhang, J.A. Hattey, W.R. Raun, and J.H. Stiegler. 1998. Science-based animal waste phosphorus management for Oklahoma. Production Technology 98-1, Dept of Plant & Soil Sciences, Oklahoma State University.

Klute, A. 1986. Methods of soil analysis, Part 1, 2nd ed. p. 404-408.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483-486.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Miller, W.P. 1987. A solenoid-operated, variable intensity rainfall simulator. Soil Sci. Soc. Am. J. 51:832-834.

Murphy, J. and J. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31.

National Phosphorus Research Project. SERA-17: Minimizing phosphorus losses from agriculture. Available at http://www.soil.ncsu.edu/sera17/ (verified 20 Feb. 2002.)

Pierzynski, G.M., J.T. Sims, and G.F. Vance. 1994. Soils and environmental quality. CRC, Boca Raton, Florida.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855-859.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.M. Miller, and D.R. Edwards. 1999. Relationship between phosphorus levels in three Ultisols and phosphorus concentrations in runoff. J. Environ. Qual. 28:170-175.

Pote, D.H., and T.C. Daniel. 2000. Analyzing for dissolved reactive phosphorus in water samples. p. 91-93. *In* G.M. Pierzynski (ed.) Methods for P analysis. Southern Cooperative Series Bulletin No. #396.

Quinton, J.N., J.A. Catt, and T.M. Hess. 2001. The selective removal of phosphorus from soil: is event size important? J. Eviron. Qual. 30:538-545.

Romkens, M.J.M. and D.W. Nelson. 1974. Phosphorus relationships in runoff from fertilized soils. J. Environ. Qual. 3:10-13.

Sauer, T.J., T.C. Daniel, D.J. Nichols, C.P. West, P.A. Moore, Jr., and G.L. Wheeler. 2000. Runoff water quality from poultry litter-treated pasture and forest sites. J. Eviron. Qual. 29:515-521.

Schoumans, O.F. 2000. Determination of the degree of phosphate saturation in non-calcareous soils. p. 31-34. *In* G.M. Pierzynski (ed.) Methods for P analysis. Southern Cooperative Series Bulletin No. #396.

Self-Davis, M.L., P.A. Moore, Jr., and B.C. Joern. 2000. Determination of water-and/or dilute salt-extractable phosphorus. p. 24-26. *In* G.M. Pierzynski (ed.) Methods for P analysis. Southern Cooperative Series Bulletin No. #396.

Sharpley, A. N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. J. Soil Water Conserv. 51:160-166.

Sharpley, A.N., S. C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: issues and options. J. Environ. Qual 23:437-451.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. J. Environ. Qual. 24:920-926.

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: historical perspective and current research. J. Environ. Qual. 27:277-293.

USDA - NRCS Soil Survey Division. Official soil series descriptions – data access [Online]. Available at http://www.statlab.iastate.edu/soils/osd/ (verified 9 Oct. 2000.)

U.S. Dept. of Commerce. 1961. Rainfall frequency atlas of the United States. Hydrologic Services Division for Engineering Division and Soil Conservation Service, U.S. Dept of Agriculture, Washington, D.C.

U.S. Environmental Protection Agency. 1998. National water quality inventory. 1998 Rep. to Congress. Office of Water, USEPA, Washington, D.C.

Wendt, R.C., and E.E. Alberts. 1984. Estimating labile and dissolved inorganic phosphate concentrations in surface runoff. J. Environ. Qual. 13:613-618.

Wolf, A.M., D.E. Bakler, H.B., Pionke, and H.M. Kunishi. 1985. Soil tests for estimating labile, soluble, and algae-available phosphorus in agricultural soils. J. Environ. Qual. 14:341-348.

Table 1.1. Soil classification and chemical and physical characteristics of three soils series evaluated

Soil Series	Classification§	pH	S_{max}‡	Clay	Sand	Silt	Organic Matter
			mg kg^{-1}	%			
Richfield	Ardic Argiustoll	7.6	312	34	21	45	1.8
Dennis	Acquic Argiudoll	7.3	189	11	30	59	2.0
Kirkland	Udertic Paleustoll	5.4	244	24	28	48	2.4

§ USDA – NRCS, 2000

‡ P sorption maximum (Smax) calculated as 1/slope of linear Langmuir P sorption isotherms

Table 1.2. Amount of fertilizer phosphorus added and mean soil phosphorus values for each treatment[†]

Soil Series	P Added	Mehlich 3 P*	Water Soluble P*	PSI$_{OX}$[‡*]	PSI$_{Smax}$[§*]
	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	%	%
Richfield	0	28 (1.7)	4.3 (0.4)	13 (1.4)	1.4 (0.13)
	235	172 (14)	32 (5.7)	26 (4.3)	10 (1.8)
	635	428 (15)	58 (14)	51 (1.0)	27 (4.4)
	1135	817 (42)	196 (21)	78 (3.2)	63 (14)
Dennis	0	35 (1.8)	3.2 (0.2)	10 (1.1)	1.7 (0.12)
	225	144 (6.7)	17 (1.6)	24 (2.6)	9.2 (0.82)
	625	411 (28)	67 (8.0)	47 (6.0)	35 (4.2)
	1125	925 (79)	230 (54)	92 (31)	122 (28)
Kirkland	0	57 (0.7)	4.0 (1.4)	11 (0.4)	1.6 (0.58)
	180	169 (12)	18 (3.3)	19 (0.2)	7.5 (1.3)
	580	478 (19)	67 (4.1)	36 (1.9)	28 (1.7)
	1080	919 (100)	146 (34)	52 (3.4)	60 (14)

†All analysis conducted after 210-day soil equilibration time

‡Ammonium Oxalate P Saturation Index (PSI$_{OX}$) based ammonium extractable P, Al and Fe

§P Sorption Saturation (PSI$_{Smax}$) based on Water Soluble and P sorption maxima

*Values reported as mean of four replications with standard deviation in parentheses

Table 1.4. Runoff dissolved reactive phosphorus (DRP) correlated to four soil phosphorus levels

Richfield Soil Series		Dennis Soil Series		Kirkland Soil Series	
	r^2		r^2		r^2
DRP=0.0046M3P - 0.14	0.95	DRP=0.0019M3P + 0.037	0.95	DRP=0.0025M3P + 0.029	0.92
DRP=0.018WSP + 0.037	0.96	DRP=0.0073WSP + 0.21	0.93	DRP=0.014WSP + 0.19	0.88
DRP=0.054PSI_{OX} - 0.72	0.91	DRP=0.019PSI_{OX} - 0.037	0.84	DRP=0.053PSI_{OX} - 0.54	0.94
DRP=0.058PSI_{Smax} - 0.37	0.96	DRP=0.025PSI_{Smax} + 0.22	0.89	DRP=0.053PSI_{Smax} + 0.54	0.94

*All r^2 values were significant ($\alpha = 0.05$)

†M3P - Soil Mehlich 3 P

‡WSP - Soil Water Soluble P

§PSI_{OX} - Ammonium Oxalate P Saturation Index

**PSI_{Smax} - P Sorption Saturation

Figure 1.1. Locations of Richfield, Kirkland and Dennis soils collected for the study.

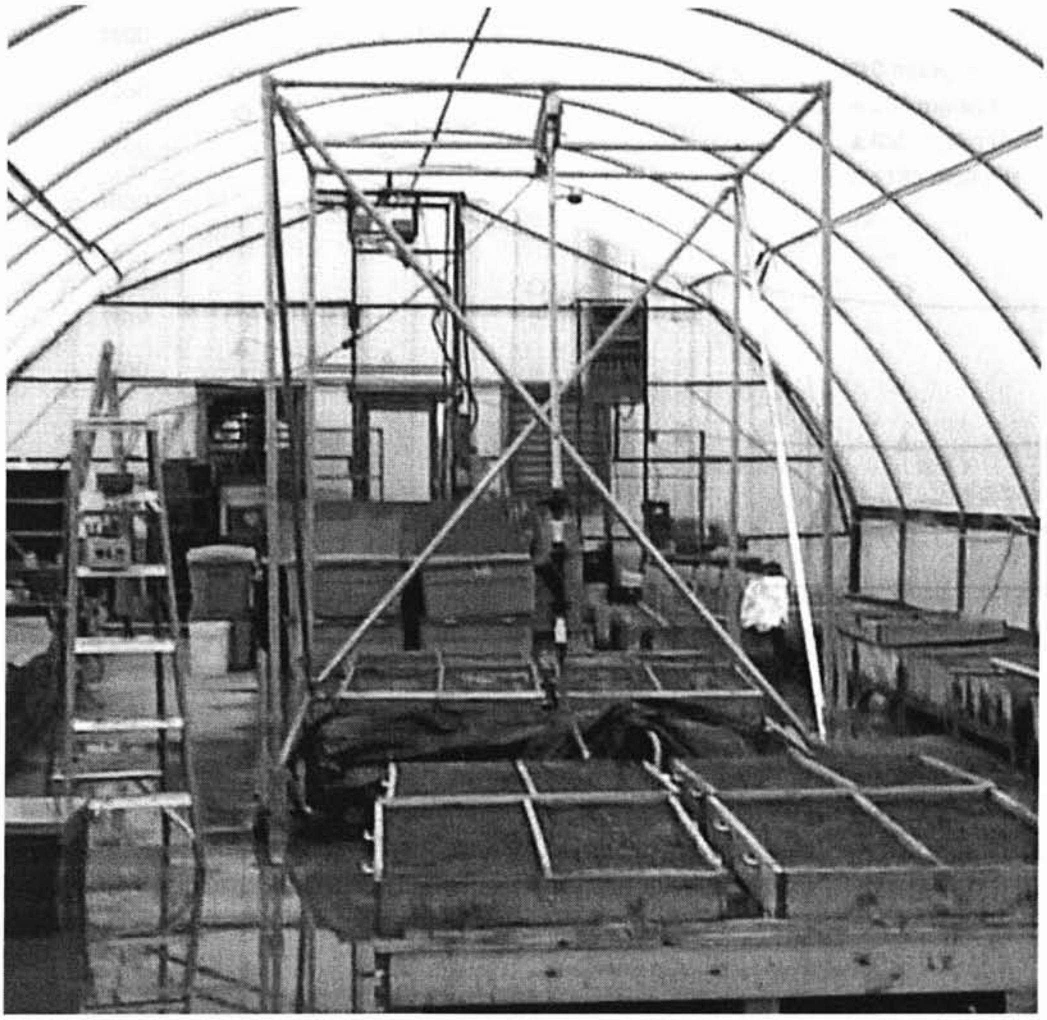

Figure 1.2. Solenoid-operated, variable intensity rainfall simulator with paired 1m x 0.42m runoff boxes.

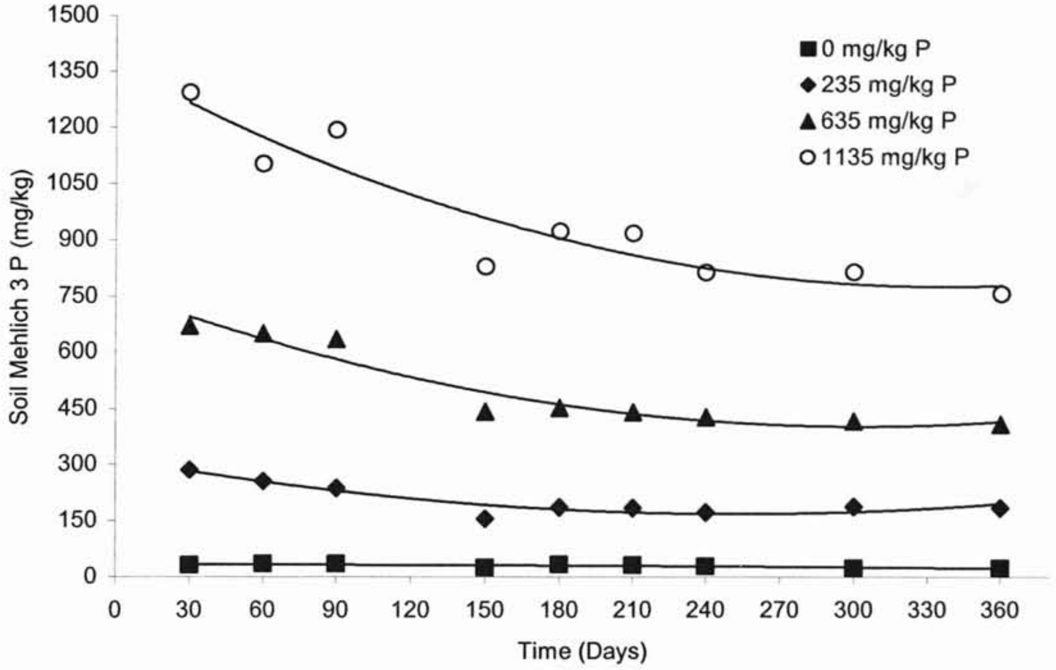

Figure 1.3. Changes in Mehlich 3 phosphorus over 360 days for four fertilizer phosphorus treatments in the Richfield soil series.

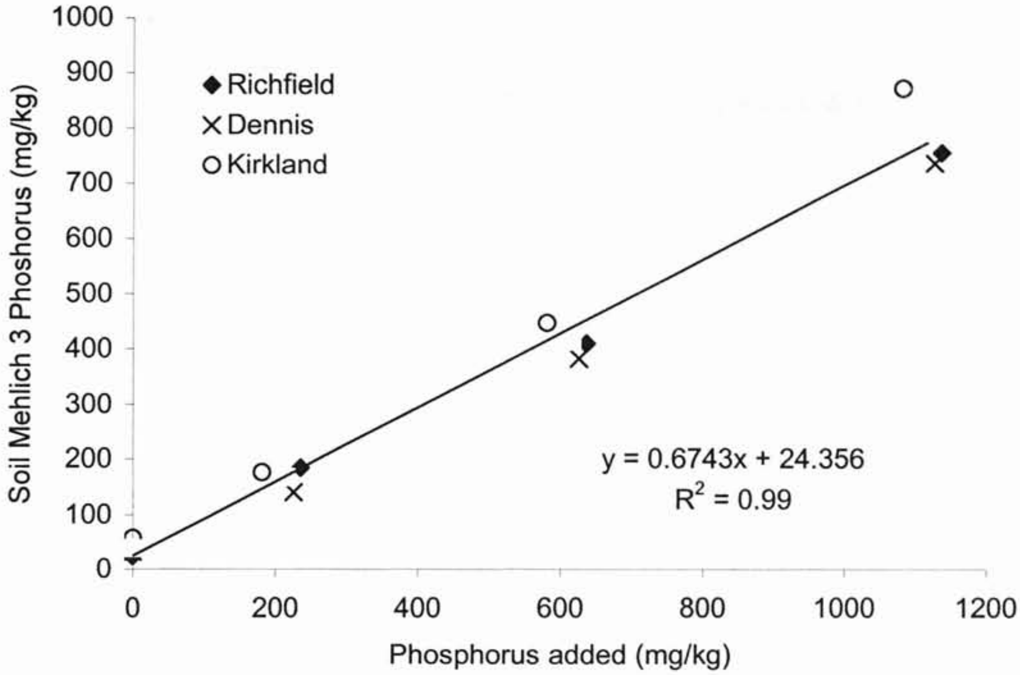

Figure 1.4. Soil Mehlich 3 phosphorus of four soil phosphorus fertilizer treatments one year after phosphorus fertilizer addition.

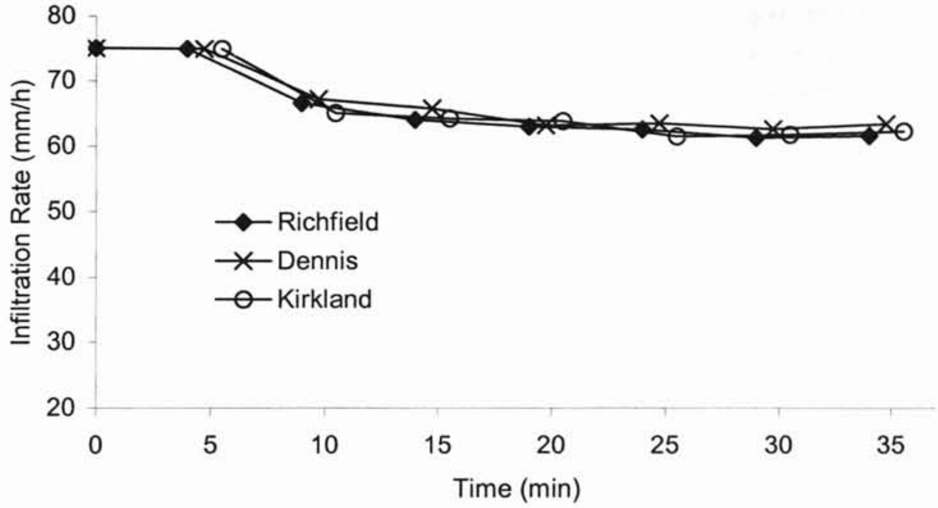

Figure 1.5. Average infiltration rate vs. time for three soil series.

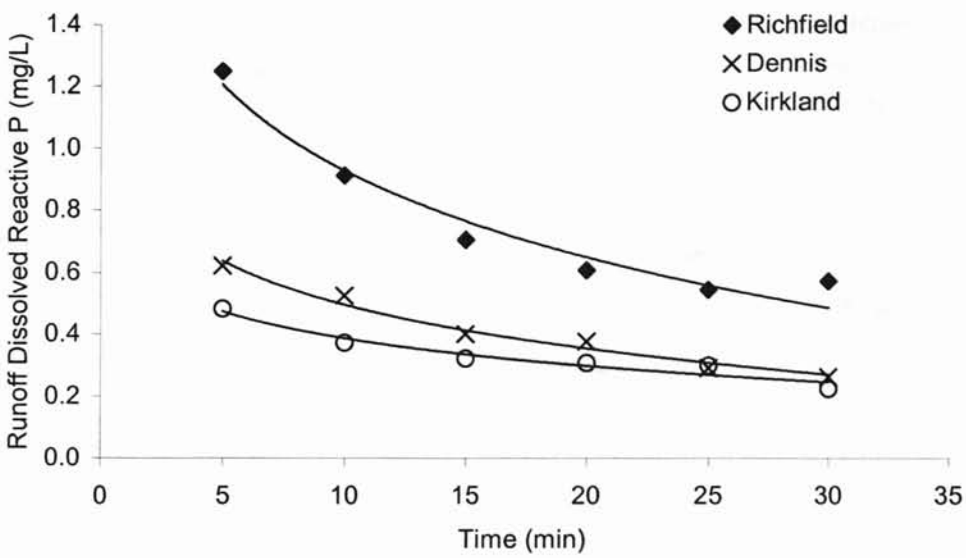

Figure 1.6. Change in runoff dissolved reactive phosphorus over 30 min. runoff duration for three soil series.

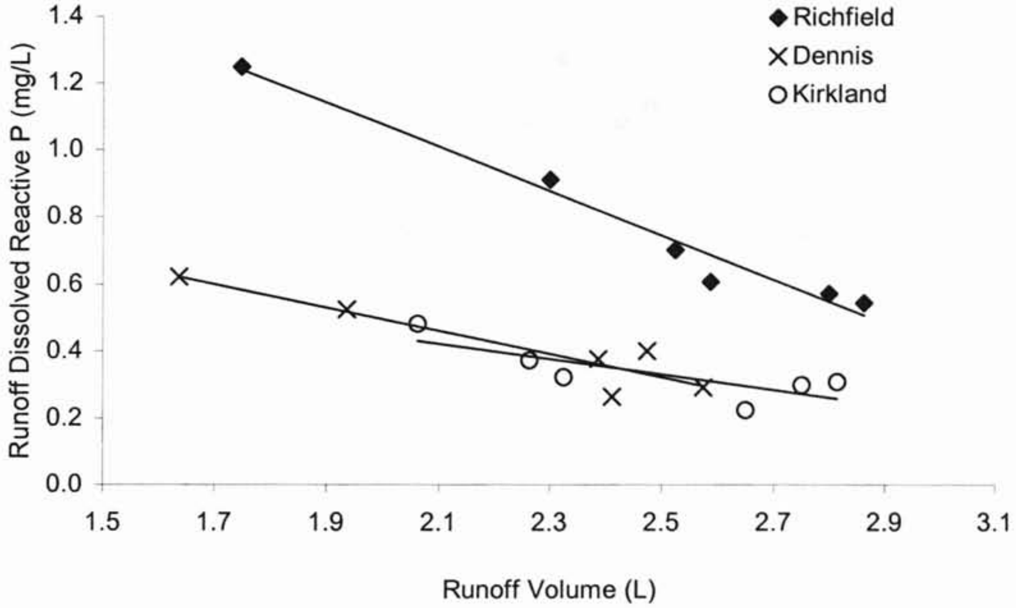

Figure 1.7. Relationship between runoff dissolved reactive phosphorus (5 min. sampling intervals) and runoff volume (5 min. sampling intervals) for three soils series.

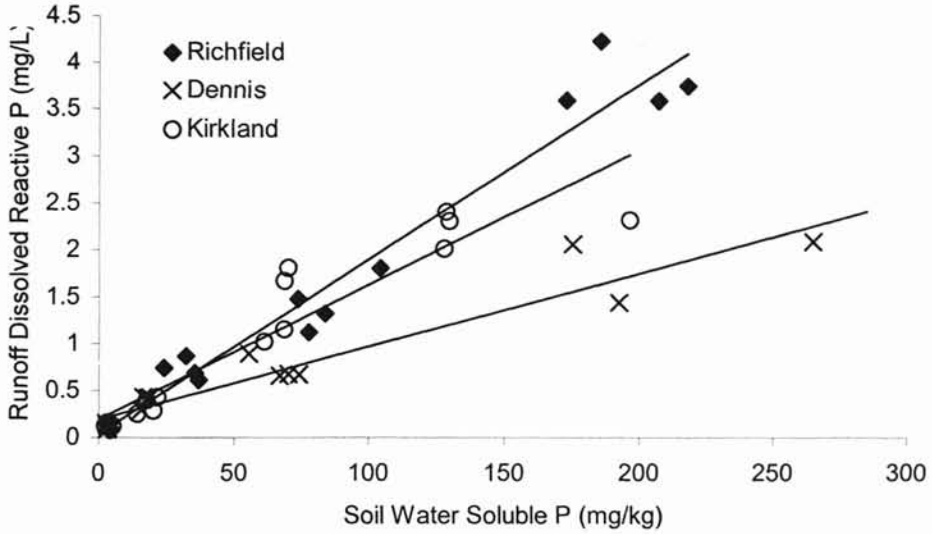

Figure 1.8. Soil specific relationships between runoff dissolved reactive phosphorus and soil water soluble phosphorus for three soil series.

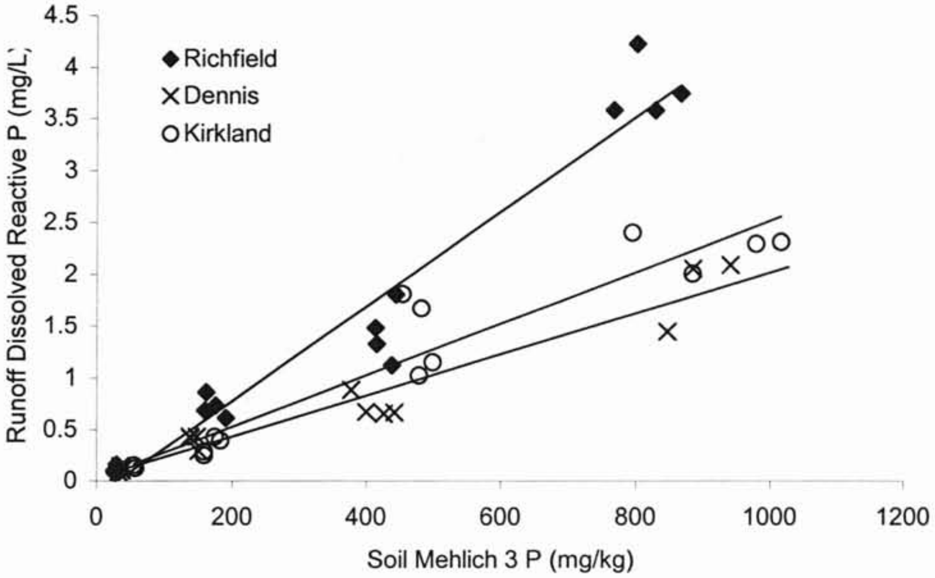

Figure 1.9. Soil specific relationships between runoff dissolved reactive phosphorus and soil Mehlich 3 phosphorus for three soil series.

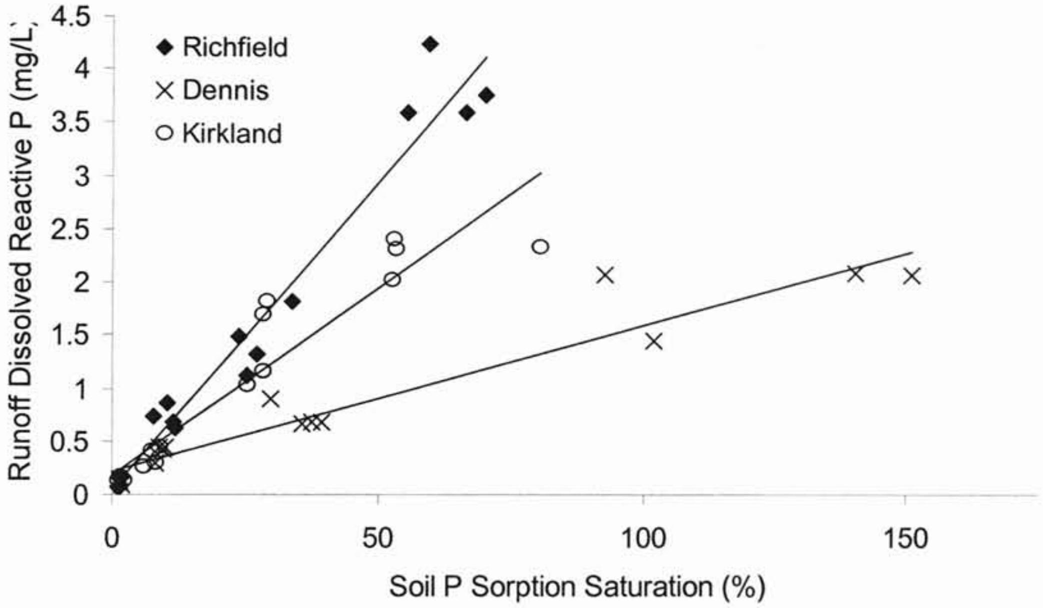

Figure 1.10. Relationship between runoff dissolved reactive phosphorus and soil phosphorus sorption saturation for three soil series.

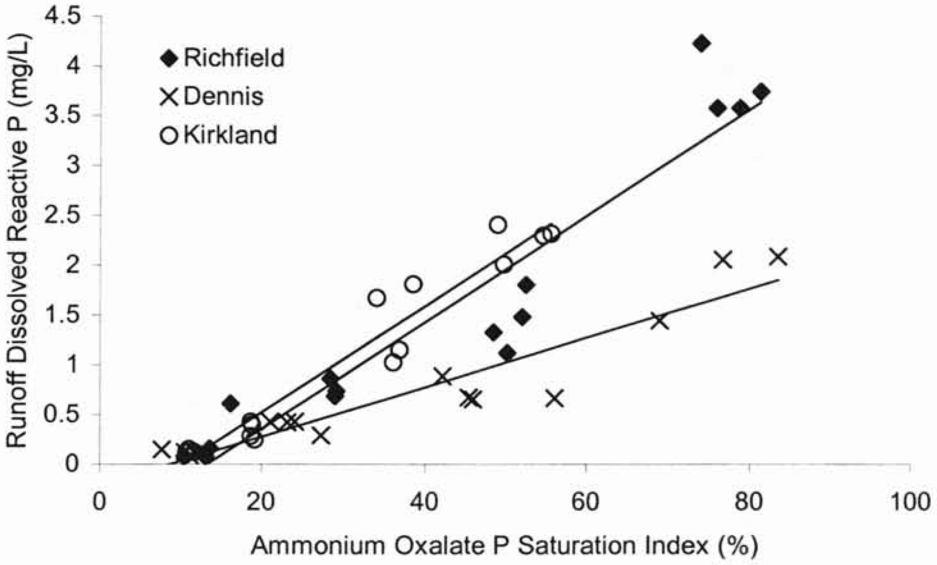

Figure 1.11. Relationship between runoff dissolved reactive phosphorus and soil ammonium oxalate phosphorus saturation index for three soil series.

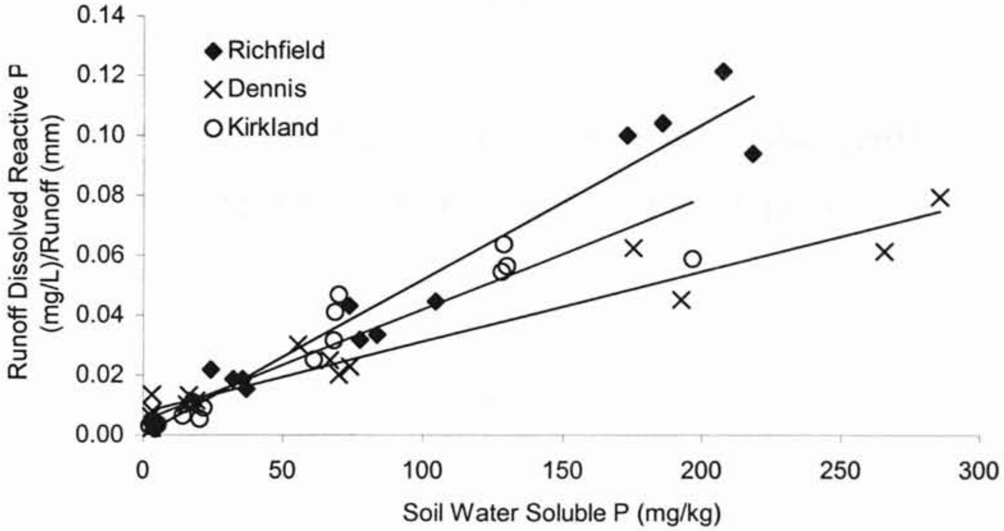

Figure 1.12. Soil specific relationships between normalized runoff dissolved reactive phosphorus and soil water soluble phosphorus for three soil series.

Chapter 2

PHOSPHORUS LOSS IN RUNOFF FROM LONG-TERM CONTINUOUS WHEAT FERTILITY TRIALS

ABSTRACT

Runoff from intensely managed winter wheat (*Triticum aestivum*) production may contain elevated levels of phosphorus (P), which can degrade surface water quality. However, limited information exists concerning the impact soil P level has on the P content of runoff from areas of long-term continuous winter wheat production. Paired 1m x 2m runoff plots were established on three existing long-term continuous winter wheat fertility experiments. Two experiments have received annual fertilizer P application at different rates since 1970, and the third one received a one-time P application at much higher rates in 1977. Simulated rain (75 mm hr^{-1}) produced 30 min. of runoff from plots with different soil test P levels; and runoff was collected and analyzed for dissolved reactive P and total P. Soil samples (0-15cm) were collected from runoff plots and analyzed for Mehlich 3 P, water soluble P, ammonium oxalate P saturation index, and P sorption saturation. Soil Mehlich 3 P ranged from 12 to 130 mg kg^{-1}. Runoff total P and dissolved reactive P (DRP) concentrations ranged from 0.47 to 1.5 mg L^{-1} and 0.07 to 0.70 mg L^{-1}, respectively. Runoff DRP was well correlated ($p<0.05$) with M3P (r^2=0.56-0.69), WSP (r^2=0.48-0.69), PSI_{OX} (r^2=0.50-0.51), and PSI_{Smax} (r^2=0.56-0.69) for all soil series tested. However, the regression equations

between DRP and soil M3P were different for different soils suggesting that soil P management strategies should be made on a soil specific basis. For a given level of soil M3P, high soil P sorption maximum coincided with low runoff DRP concentrations. This suggests the importance of a soil's ability to retain P in determining P loss in runoff.

INTRODUCTION

Phosphorus (P) loss from intensely managed agro-ecosystems is often associated with accelerated eutrophication and algal blooms in lakes and other surface water bodies (Zemenchik et al., 2002). Over the past 25 yr., the amount of plant-available P in some soils have increased substantially from excessive P fertilizer and manure application (Bundy et al., 2001). When elevated soil P levels coincide with zones of surface runoff, elevated soil P levels can account for most of the total annual load of P in surface water (Edwards et al., 1993). Consequently, controlling agricultural non-point source (NPS) P loss is of great concern to minimize surface water degradation (USEPA, 1998).

At present, a large amount of P runoff information deals with animal manure applications. Mueller et al. (1984) compared runoff P from varying tillage systems for corn and found that surfacing spreading manure increased runoff dissolved reactive P (DRP). Cox and Hendricks (2000) found that two Ultisols amended with poultry litter increased in soil Mehlich 3 P and runoff DRP. Sauer et al. (2000) found that poultry litter treated plots had higher concentrations of runoff P compared to untreated pasture and forested runoff plots.

Researchers have also compared runoff P from varying tillage and cropping systems receiving commercial P fertilizers. Romkens et al. (1973) working with corn, found that reduced tillage systems decreased sediment nutrient losses but increased runoff dissolved P concentrations when compared to conventional tillage. Gascho et al. (1998) also working with corn, found that runoff P losses were greatest one day after commercial P fertilizer application.

Sharpley et al (1991) stated that conservation tillage reduced sediment and P transport in runoff relative to conventional tillage while working with sorghum in the Southern Plains. Douglas et al. (1998) found that runoff P was higher for continuous fallow than for both winter wheat and spring pea cropping systems.

Additionally, earlier runoff P - soil P experiments were conducted on soils amended with P fertilizer or manure to establish a wide range of soil P levels. Often times, these fertilizer or manure amendments are applied shortly before the data were collected resulting in a relatively short time period for the fertilizer or manure amendment to react with the soil. Reddy et al. (1978), using soil micro-plots amended with manure and commercial fertilizers that were incubated for 23 days, found that runoff P loss increased with increased chemical P and manure applications. Edwards and Daniel (1993) applied simulated rainfall to soil plots 24 hr. after manure application and found that runoff P increased with increased manure application. Bundy et al. (2001) found that P in runoff collected from no-till corn production plots that had received manure and biosolids for 5 yr. increased as Bray 1 P increased. Cox and Hendricks (2000) found that runoff DRP losses increased with recent fertilizer P application in wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) production.

However, there are few studies that involve experimental soils or sites that have been under long-term fertilizer P application and have been under long-term continuous winter wheat (*Triticum aestivum*) cultivation. Consequently, the relationship between soil P and runoff P in soils under long-term continuous winter wheat cultivation receiving chemical fertilizer has not been thoroughly researched. The objective of this study is to evaluate the relationship between runoff P and soil P on three Oklahoma soils that have been under continuous wheat production and have received long-term P fertility treatments for over 30 years.

MATERIALS AND METHODS

Rainfall Simulation Sites

Three sites (Lahoma, Stillwater, and Haskell research stations) were chosen from existing long-term fertility research plots located across Oklahoma to evaluate the relationship between runoff P and soil P (Figure 2.1). The Lahoma site (long-term fertility experiment #502) was established on a Grant silt loam in the fall of 1970 (Raun et al., 2000) with five fertilizer P (triple super phosphate, 0-46-0) application rates (0-40 kg P ha^{-1}, 5 treatments) on an annual basis and has been under continuous winter wheat (*Triticum aestivum*) cultivation (Table 2.2). The last P fertilization was about one year before rainfall simulation took place.

The Stillwater site (long-term fertility experiment #222) was established on a Kirkland loam in 1969 (Raun et al., 2000) with four fertilizer P (triple super phosphate, 0-46-0) application rates (0-44 kg P ha^{-1}, 4 treatments) on an annual basis and has been under continuous winter wheat (*Triticum aestivum*) cultivation for 31 years (Table 2.2). The last P fertilization was also about one year before rainfall simulation.

The Haskell site (long-term fertility experiment #802) was established in the fall of 1977 on a Taloka silt loam (Raun et al., 2000) with four, one time fertilizer P, (triple super phosphate, 0-46-0) application rates (0-587 kg P ha^{-1}, 4 treatments) in the fall of 1977 (Table 2.2). In addition, winter wheat (*Triticum aestivum*) has been planted for 23 continuous years. To alleviate soil acidity problems, lime was applied for two consecutive years (July 1998 and July 1999) at a rate of 1600kg ECCE ha^{-1} (Raun et al., 2000).

Runoff Plots

At each of the three sites, two sets of paired runoff plots were established on each P rate treatment (5-Stillwater, 4-Lahoma, 4-Haskell) to give four replications per treatment and 52 total runoff plots. Each site was disked before 1m x 2m runoff plots were established using 0.2cm x 15cm metal strips installed to a depth of 10 cm on 5% sloped fertility plots. Runoff gutter was installed on the down-slope end of the plot to collect runoff. In addition, paraffin wax was used to seal runoff gutter to soil to prevent runoff loss underneath and around the gutter. Plexi-glass strips were placed over guttering to prevent rainfall from falling directly into runoff gutter while still allowing runoff collection. Twenty-four hr. prior to rainfall simulation, all runoff plots were irrigated until saturated.

Rainfall Simulation

Rainfall simulations were conducted at the Stillwater and Lahoma sites during August 2000 and the Haskell rainfall simulation was conducted during August 2001. Simulated rainfall was applied using a portable, solenoid-operated, variable intensity rainfall simulator based on the design of Miller (1987) (Fig. 2.2) with one TeeJet^{TM} ½ HH-SS50WSQ nozzle placed in the center of the 3m H x 2.8m L x 2.3m W aluminum frame. The rainfall simulator was calibrated to deliver 75 mm hr^{-1}, which is in accordance with the protocol recommended by the National Phosphorus Research Project (NPRP) and equivalent to a 10-year storm event in north-central Oklahoma (USDC, 1961). The intensity of the rainfall was controlled by the on-off (1.3 s on; 0.4 s off) spraying times of the nozzle. Water was supplied to the simulator from a 500 gal water tank that was filled from the respective research station's potable well water source.

At each experimental site, simulated rainfall was applied to runoff plots until 30 min. of measurable runoff was collected. Peristaltic pumps were used to transfer runoff collected in each gutter to 35 L collection containers. The accumulative runoff volume was recorded every five min. for 30 min.. Collected runoff was manually agitated to homogenously re-suspend sediment before one representative runoff sample (500 ml) was obtained from each runoff plot for P analysis. Runoff samples were stored at 4°C until lab analyses were performed.

Soil and Runoff Analyses

Shortly after rainfall simulations, soil samples (0-15cm) were collected for characterization and for correlation with runoff P. Mehlich 3 extractable P (M3P, Mehlich, 1984), water soluble P (WSP, Self-Davis et al., 2000), P sorption maxima, ammonium oxalate extractable P, Al and Fe, texture, soil organic matter (OM), and pH were determined for the three soils series evaluated. Soil characterization results are summarized in Table 2.1. Phosphorus sorption isotherms were constructed by shaking (end-over-end, 24 hr.) 1 g soil with 25 ml of the following concentrations of P in 0.01 M $CaCl_2$ solution: 0, 0.5, 1, 5, 10, 15, 20, 25, 40, and 50 mg/L (Graetz and Nair, 2000). The samples were centrifuged at 10,000 rpm (14,470 x g) for 5 min., filtered (0.45 μm), and analyzed for P colorimetrically (Murphy and Riley, 1962). Phosphorus sorption maximum

(Smax) was determined as 1/slope of the linear Langmuir equation of the isotherm for each soil (Graetz and Nair, 2000).

Mehlich 3 P was extracted by shaking (end-over-end, 5 min.) 2 g of each soil with 20 ml of extractant (Mehlich, 1984). Extracts were filtered (Whatman #4) and analyzed colorimetrically (Murphy and Riley, 1962). In addition, P sorption saturation (PSI_{Smax}) was computed using WSP and Smax (mg kg^{-1}) by the following equation (Sharpley, 1995):

$$PSI_{Smax}\,(\%) = (WSP/\,Smax)*100 \qquad [eq.\ 1]$$

Soil WSP was extracted by shaking 2 g of soil (end-over-end, 1 hr.) with 20 ml of distilled water and centrifuging at 10,000 rpm (14,470 x g) for 5 min. (Self-Davis et al., 2000). The supernatant was filtered (0.45 µm), and analyzed for P colorimetrically (Murphy and Riley, 1962).

Ammonium oxalate extractable P, Al, and Fe were also measured. Thirty ml of ammonium oxalate solution (16.2 g ammonium oxalate monohydrate, 10.8 g oxalic acid dihydrate made to one L with deionized water; Schoumans, 2000) was shaken (end-over-end, 2 hr.) with 1.5 g of soil, filtered (Whatman #4), and analyzed for P, Al, and Fe using an ICP-AES. Phosphorus saturation index by ammonium oxalate extraction (PSI_{OX}) was computed using the P, Al, and Fe contents (mmol kg^{-1}) by the following equation (Schoumans, 2000):

$$PSI_{OX}\,(\%) = ([P]/\,[Fe + Al])*100 \qquad [eq.\ 2]$$

Soil texture was determined using the hydrometer method (Gee and Bauder, 1986). Soil pH was determined using a glass electrode at a 1:1 soil/ water ratio (w/v). Soil organic matter was determined using a modified loss-on-ignition method described by Ben-Dor and Banin (1989) in which 2 g of soil was placed in a 150°C oven to remove moisture (2 hr.), weighed (W1) then placed in a 425°C oven to remove organic matter (2 hr.) and weighed again (W2). Soil organic matter was calculated using the following equation:

$$OM (\%) = [(W1 - W2)/ W2]*100 \qquad [eq. 3]$$

Immediately after rainfall simulation, an aliquot from every runoff water sample was filtered (0.45μm) and analyzed colorimetrically to determine dissolved reactive P (DRP, Pote and Daniel, 2000). Total P (TP) from each runoff sample was determined by digesting 25 ml of runoff at 175°C with 1 ml concentrated H_2SO_4 and 5 ml concentrated HNO_3 until a total volume of 1 ml remained (Pote and Daniel, 2000). All digested samples were neutralized and analyzed for P colorimetrically (Murphy and Riley, 1962). Particulate P (PP) was calculated by subtracting DRP from TP. Runoff TP and DRP loads (mg) were computed by multiplying DRP and TP concentration (mg L^{-1}) by total runoff volume (L).

Total suspended solids (TSS) were determined for all runoff water samples by vacuum filtering (0.45μm) 50 ml of well-mixed runoff water sample and drying the vacuum filter cup and filter paper at 95°C. The initial dry weight of the vacuum cup and filter was subtracted from the final dry weight of the sediment, vacuum cup and filter to give TSS. Runoff TSS load (mg) was calculated by multiplying TSS (mg L^{-1}) by runoff volume (L) of each treatment.

Statistical Analysis

Simple linear regression was used to correlate runoff DRP and TP concentrations with four types of soil P levels for all plots. The strengths of these correlations were expressed by the coefficient of determination (r^2 value). These data were also tested for significance among the three soil series evaluated using analysis of covariance.

RESULTS AND DISCUSSION

Soil Phosphorus

Using P adsorption isotherms, it was found that the Kirkland soil had the greatest P sorption capacity (263 mg kg^{-1}) followed by the Taloka soil (227 mg kg^{-1}) and the Grant soil (175 mg kg^{-1}). In addition, the annual application of commercial P fertilizers on the Kirkland and Grant soils and the large one-time application of P fertilizer on the Taloka soil resulted in a wide range (12-130 mg kg^{-1}) of soil M3P (Table 2.2). Soil M3P and WSP was linearly related ($p<0.05$) to P application rate ($r^2=0.95-0.99$; $r^2=0.86-0.99$, respectively). As soil WSP generally constituted a small portion of soil M3P, a minimal amount of free P existed in soil. In addition, PSI_{OX} and PSI_{Smax} were determined to estimate the amount of soil P as a percent of the amount of P that can be held by the soil. Both indices were low for all treatments, but were well correlated ($r^2>0.95$; $p<0.05$) to P fertilizer application rate for all soils evaluated.

Rainfall Simulation and Runoff

Rainfall simulation source water used in this study had relatively low TP and DRP concentrations in comparison to runoff TP and DRP. Water used on the Grant, Kirkland, and Taloka soils averaged 0.10, 0.04, and 0.07 mg L^{-1} TP, respectively. Simulated rainfall was applied to runoff plots 24 hr. after the plots were saturated. Rainfall infiltrated the soil surface and collected in small pondings before measurable runoff was observed. Time from the start of rain to measurable runoff began ranged from 4 to 12 min. among all treatment and soils.

All three runoff study sites had virtually no surface cover except for small amounts of wheat stubble (<5%) and had similar surface slopes (5%). The Grant series began runoff quicker on average than the other 2 soil series evaluated. The Grant and Taloka soils exhibited similar infiltration rates and runoff volumes and the Kirkland soil exhibited the lowest average infiltration rates and greatest average runoff volumes (Table 2.3, Figure 2.3).

Total suspended solids (TSS) concentrations in the runoff were similar among three soil series (Table 2.3). However, as runoff volumes were greatest for the Kirkland series, TSS load (the total amount of suspended sediment lost, mg) was greatest for the Kirkland soil (data not shown). Runoff total P (TP) was well correlated (r^2=0.88; $p<0.05$) to runoff TSS for the Kirkland soil, but weakly correlated to runoff TSS for the Taloka (r^2=0.21) and Grant soils (r^2=0.18) (Fig. 2.4). Runoff TP concentrations were similar for the three soil series tested (Table 2.3). However, as the Kirkland soil produced the greatest overall runoff volume, it also lost the greatest average amount (load, mg) of P in runoff (Table 2.3). This suggests that the Kirkland soil would pose the greatest overall risk of P loss in runoff among all three soil series evaluated.

Relationship between Runoff TP and Soil P

In this study, soil Mehlich 3 P (M3P), soil water soluble P (WSP) ammonium oxalate P saturation index (PSI_{OX}), and P sorption saturation (PSI_{Smax}) served as poor predictors of runoff TP concentrations for the Grant and Taloka soil series (Table 2.4). However, runoff TP from the Kirkland soil was well correlated with soil M3P (r^2=0.66), WSP (r^2=0.61), PSI_{OX} (r^2=0.72), and PSI_{Smax}

(r^2=0.66) (Table 2.4). It is important to note that particulate P (PP) constituted the majority of TP lost in runoff from all three soil series. This is consistent with that found by other researchers under similar runoff conditions (Romkens and Nelson, 1974; Reddy et al., 1978; Sharpley, 1997). Particulate P on average accounted for 93, 83, and 70% of TP lost in runoff from the Kirkland, Taloka, and Grant soils, respectively (Table 2.3). No significant differences in % PP were detected between treatments within each soil series.

Relationship between Runoff DRP and Soil P

Runoff dissolved reactive P (DRP), the portion of runoff TP that is immediately bioavailable, was well correlated ($p<0.05$) with M3P (r^2=0.56-0.69), WSP (r^2=0.48-0.69), PSI_{OX} (r^2=0.50-0.51), and PSI_{Smax} (r^2=0.48-0.69) for all soil series tested (Table 2.5). Of the soil P values tested here (M3P, WSP, PSI_{OX}, and PSI_{Smax}), soil M3P was the most highly correlated ($r^2>0.56$) to runoff DRP for all three soils (Fig. 2.5; Table 2.5). Judging by the coefficient of determination (r^2 value), the relationship between runoff DRP and soil P was stronger for the Grant and Taloka soils than for the Kirkland soil. It should also be noted that DRP constituted a greater proportion of TP for the Grant (30%) and Taloka (17%) soils than for the Kirkland soil (7%). This suggests that when DRP constitutes a significant portion of runoff TP (i.e. > 17%), soil P would serve as better predictors of runoff DRP concentrations than when DRP constituted a small portion of the runoff TP.

The relationship between runoff DRP and M3P was significantly different ($p<0.05$) for the Grant and Kirkland soils. Although no other significant differences were observed, the slopes of the relationships between runoff DRP and soil M3P for the three soils varied widely. This suggests that runoff DRP – soil M3P relationships used in P management strategies will probably have to be soil specific. For example, the Kirkland soil (27% clay, Smax 263 mg kg^{-1}) produced a runoff DRP concentration of 0.09 mg L^{-1} at a soil M3P level of 50 mg kg^{-1}while the Grant soil (25 % clay, Smax 175 mg kg^{-1}) produced a runoff DRP concentration of 0.3 mg L^{-1} at the same soil M3P level. As the Kirkland soil series has a larger Smax than the other two soils, DRP concentrations in runoff were consistently lower than for the remaining soils.

In this study, Smax seemed to be the soil property most related to the runoff DRP. Phosphorus sorption maximum (Smax) is the maximum amount of P that a particular soil may hold. For example, the Grant soil had the lowest Smax (175 mg ha-1) and released the greatest amount of runoff DRP per unit soil M3P in comparison to the remaining two soils. This is consistent with that found by other researchers.

The slopes of the relationship between runoff DRP and soil M3P ranged from 0.0016 to 0.0045. The slopes of the same relationship on pasture lands (0.0016-0.0035) and forested lands (0.014) are considerably different (Pote et al., 1999; Sauer et al., 2000). In a similar study, Cox and Hendricks (2000) found that runoff DRP – soil M3P relationship slopes varied (0.0014 to 0.0040) in conventional and no-till wheat and barley cropping systems. This suggests that land use and management practices can also greatly affect the relationship between soil M3P and runoff DRP. As a result, P management recommendations should consider land use and management.

CONCLUSIONS

Due to commercial P fertilizer application, a wide range of soil P levels was observed in the three long-term continuous wheat fertility trials evaluated. Additionally, soil P level was well correlated with commercial P fertilizer application rate at all three sites evaluated. Runoff TP concentrations were similar for all soil series evaluated though not well correlated to soil test P. Of the soil series tested, the Kirkland soil produced the greatest runoff volume and the lowest overall infiltration rate. As a result, the Kirkland soil lost the highest total amount of P in runoff. This suggests that the Kirkland soil would pose the greatest overall risk of P loss in runoff when compared to the other two soils evaluated in this study.

Runoff DRP was well correlated to soil M3P, WSP, PSI_{OX}, and PSI_{Smax}. It was also found that when runoff DRP constitutes a large percentage of runoff TP, the relationship between runoff DRP and soil M3P improves. However, the slopes of the relationship between runoff DRP and soil M3P varied considerably across soils evaluated within this study. The Smax property of soil seemed to be responsible for the observed variation in the relationship between runoff DRP and soil M3P among different soils. For example, the soil with the lowest Smax (the Grant soil) released the highest concentration of runoff DRP per unit soil P while the soil with the highest Smax (the Kirkland soil) released the lowest concentration of runoff DRP per unit soil P.

In comparison to the work of others on pasture, forest, and cultivated sites, it was found that the slope of the regression line between runoff DRP and soil M3P varies not only with soil type but also with land use and management practices and type and method of fertilizer P application. This suggests that P management recommendations must be made on a site-specific basis and include factors such as land use and management practices.

REFERENCES

Ben-Dor, E., and A. Banin. 1989. Determination of organic matter content in arid-zone soils using a simple "loss-on-ignition" method. Commun. Soil Sci. Plant Anal. 20:1675-1695.

Bundy, L.G., T.W. Andraski, and J.M. Powell. 2001. Management practice effects on phosphorus losses in runoff in corn production systems. J. Environ. Qual. 30:1822-1828.

Cox, F.R., and S.E. Hendricks. 2000. Soil test phosphorus and clay content effects on runoff water quality. J. Environ. Qual. 29:1582-1586.

Daniel, T.C., A.N. Sharpley, and J.L. Lemunyon. 1998. Agricultural phosphorus and eutrophication: A symposium overview. J. Environ. Qual. 27:251-257.

Douglas, C.L., K.A. King, and J.F. Zuzel. 1998. Nitrogen and phosphorus in surface runoff and sediment from a wheat-pea rotation in northeastern Oregon. J. Environ. Qual. 27:1170-1177.

Edwards, D.R. and T.C. Daniel. 1993. Effects of litter application rate and rainfall intensity on quality of runoff from fescue grass plots. J. Environ. Qual. 22:361-365.

Gascho, G.J., R.D. Wauchope, J.G. Davis, C.C. Truman, C.C. Dowler, J.E. Hook, G.R. Sumner, and A.W. Johnson. 1998. Nitrate-nitrogen, soluble, and bioavailable phosphorus runoff from simulated rainfall after fertilizer application. Soil Sci. Soc. Am. J. 62:1711-1718.

Gaynor, J.D. and W.I. Findlay. 1995. Soil and phosphorus loss from conservation and conventional tillage in corn production. J. Environ. Qual. 24:734-741.

Gee, G.W. and J.W. Bauder. 1986. Particle Size Analysis. P383-411. *In* A. Klute (ed.) Methods of soil analysis; Part 1 Physical and mineralogical methods 2nd ed. American Society of Agronomy. Agronomy Monograph no. 9.

Graetz, D.A., and V.D. Nair. 2000. Phosphorus sorption isotherm determination. p. 35-38. *In* G.M. Pierzynski (ed.) Methods for P analysis. Southern Cooperative Series Bulletin No. #396.

Hooda, P.S., A.R. Rendell, A.C. Edwards, P.J.A. Withers, M.N. Aitken, and V.W. Truesdale. 2000. Relating soil phosphorus indices to potential phosphorus release to water. J. Environ. Qual. 29:1166-1171.

Lemunyon, J.L., and Gilbert. 1993. The concept and need for a phosphorus assessment tool. J. Prod. Agric., 6:483-486.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Miller, W.P. 1987. A solenoid-operated, variable intensity rainfall simulator. Soil Sci. Soc. Am. J. 51:832-834.

Murphy, J. and J. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31.

National Phosphorus Research Project. SERA-17: Minimizing phosphorus losses from agriculture. Available at http://www.soil.ncsu.edu/sera17/ (verified 20 Feb. 2002.)

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.M. Miller, and D.R. Edwards. 1999. Relationship between phosphorus levels in three Ultisols and phosphorus concentrations in runoff. J. Environ. Qual. 28:170-175.

Pote, D.H., and T.C. Daniel. 2000. Analyzing for dissolved reactive phosphorus in water samples. p. 91-93. *In* G.M. Pierzynski (ed.) Methods for P analysis. Southern Cooperative Series Bulletin No. #396.

Raun, W.R., G.V. Johnson, and R.L. Westerman. 2000. Soil fertility research highlights 2000. Oklahoma State University, Department of Plant & Soil Sciences.

Reddy, G.Y., E.O. McLean, G.D. Hoyt, and T.J. Logan. 1978. Effects of soil, cover crop, and nutrient source on amounts and forms of phosphorus movement under simulated rainfall conditions. J. Environ. Qual. 7:50-54.

Romkens, M.J.M., D.W. Nelson, and J.V. Mannering. 1973. Nitrogen and phosphorus compositions of surface runoff as affected by tillage method. J. Eviron. Qual. 2:292-295.

Romkens, M.J.M. and D.W. Nelson. 1974. Phosphorus relationships in runoff from fertilized soils. J. Environ. Qual. 3:10-13.

Sauer, T.J., T.C. Daniel, D.J. Nichols, C.P. West, P.A. Moore, Jr., and G.L. Wheeler. 2000. Runoff water quality from poultry litter-treated pasture and forest sites. J. Eviron. Qual. 29:515-521.

Schoumans, O.F. 2000. Determination of the degree of phosphate saturation in non-calcareous soils. p. 31-34. *In* G.M. Pierzynski (ed.) Methods for P analysis. Southern Cooperative Series Bulletin No. #396.

Self-Davis, M.L., P.A. Moore, Jr., and B.C. Joern. 2000. Determination of water- and/or dilute salt-extractable phosphorus. p. 24-26. *In* G.M. Pierzynski (ed.) Methods for P analysis. Southern Cooperative Series Bulletin No. #396.

Sharpley, A.N. S.J. Smith, J.R. Williams, O.R. Jones, and G.A. Coleman. 1991. Water quality impacts associated with sorghum culture in the Southern Plans. J. Eviron. Qual. 20:239-244.

Sharpley, A. N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. J. Soil Water Conserv. 51:160-166.

Sharpley, A.N. 1997. Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter. J. Environ. Qual. 26:1127-1132.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. J. Environ. Qual. 24:920-926.

U.S. Dept. of Commerce. 1961. Rainfall frequency atlas of the United States. Hydrologic Services Division for Engineering Division and Soil Conservation Service, U.S. Dept of Agriculture, Washington, D.C.

U.S. Environmental Protection Agency. 1998. National water quality inventory. 1998 Rep. to Congress. Office of Water, USEPA, Washington, D.C.

U. S. Environmental Protection Agency, Office of Water. 2000. Overview of current total maximum daily load –TMDL- program and regulations [Online]. Available at http://www.epa.gov/owow/tmdl/overviewfs.html (verified 23 Jan. 2001.)

Zemenchik, R.A., N.C. Wollenhaupt, and K.A. Albrecht. 2002. Bioavailable phosphorus in runoff from alfalfa, smooth bromegrass, and alfalfa-smooth bromegrass. J. Environ. Qual. 31:280-286.

Table 2.1. Soil Classification and chemical and physical characteristics of long-term fertility runoff plots

Soil Series	Classification§	pH	S_{max}‡	Clay	Sand	Silt	Organic Matter
			mg kg^{-1}	%			
Grant	Udic Argiustoll	5.1	175	25	25	50	1.9
Kirkland	Udertic Paleustoll	5.4	263	27	20	53	2.3
Taloka	Mollic Albaqualf	7.0	227	19	28	53	1.6

§ USDA – NRCS, 2000

‡ P sorption maximum (Smax) calculated as 1/slope of linear Langmuir P sorption isotherms

Table 2.2. Fertilizer phosphorus rates and mean soil phosphorus values for long-term fertility runoff plots

Soil Series	P Added	Mehlich 3 P	Water Soluble P	PSI_{OX}‡	PSI_{Smax}§
	kg ha^{-1}	mg kg^{-1}	mg kg^{-1}	%	%
Grant †	0 (0)	19 (1.3)	0.95 (0.06)	7.2 (0.34)	0.54 (0.03)
	290 (10)	42 (6.1)	2.8 (0.84)	9.7 (0.71)	1.6 (0.43)
	638 (22)	66 (4.5)	5.3 (0.77)	13 (0.53)	3.0 (0.44)
	841 (29)	77 (11)	6.7 (1.5)	13 (0.61)	3.8 (0.34)
	1160 (40)	130 (18)	16 (2.1)	16 (2.8)	9.0 (1.2)
Kirkland †	0 (0)	15 (2.5)	0.95 (0.13)	5.0 (1.1)	0.36 (0.07)
	465 (15)	38 (2.1)	2.3 (0.22)	7.1 (0.42)	0.87 (0.03)
	930 (30)	66 (6.4)	3.9 (0.44)	9.1 (0.74)	1.5 (0.17)
	1364 (44)	85 (3.7)	5.1 (1.4)	12 (0.55)	1.9 (0.54)
Taloka ‡	0	12 (0.41)	0.70 (0.10)	5.9 (0.42)	0.31 (0.05)
	117	13 (0.65)	0.93 (0.17)	6.4 (0.42)	0.41 (0.03)
	293	27 (0.85)	2.0 (0.23)	8.0 (0.66)	0.86 (0.10)
	587	45 (7.9)	3.0 (0.64)	11 (1.3)	1.3 (0.23)

† Total amount of P applied over the duration of the fertility experiment with yearly application in parentheses

‡ P rates applied once in 1977

§Ammonium Oxalate P Saturation Index (PSI_{OX})

*P Sorption Saturation (PSI_{Smax})

** Values reported as mean of four replications with standard deviation in parentheses

Table 2.3. Mean runoff water sample characteristics collected from long-term fertility runoff plots

Soil Series	P Added	Volume	Total Suspended Solids	Dissolved Reactive P	Particulate P	Total P
	—kg ha^{-1}—	—L—	—mg L^{-1}—	—mg L^{-1}—	—mg L^{-1}—	—mg L^{-1}—
Grant †	0 (0)	31 (1.1)	2.5 (0.5)	0.14 (0.02)	1.1 (0.11)	1.2 (0.12)
	290 (10)	35 (12)	2.6 (0.3)	0.27 (0.03)	0.87 (0.27)	1.1 (0.26)
	638 (22)	31 (1.0)	2.4 (0.6)	0.33 (0.03)	0.85 (0.15)	1.2 (0.17)
	841 (29)	24 (10)	2.4 (1.0)	0.44 (0.03)	1.1 (0.38)	1.5 (0.32)
	1160 (40)	27 (5.2)	1.9 (0.7)	0.70 (0.10)	0.61 (0.24)	1.3 (0.23)
Kirkland †	0 (0)	55 (10)	1.4 (0.1)	0.03 (0.00)	0.56 (0.06)	0.56 (0.06)
	465 (15)	57 (8.4)	2.4 (0.3)	0.06 (0.01)	1.1 (0.08)	1.2 (0.03)
	930 (30)	44 (5.2)	2.2 (0.7)	0.12 (0.03)	0.98 (0.18)	1.1 (0.13)
	1364 (44)	43 (12)	3.5 (0.7)	0.13 (0.03)	1.90 (0.42)	2.0 (0.43)
Taloka ‡	0	35 (3.4)	2.5 (0.7)	0.07 (0.02)	0.80 (0.31)	0.87 (0.29)
	117	26 (16)	1.8 (0.7)	0.10 (0.02)	0.36 (0.15)	0.47 (0.14)
	293	28 (6.3)	1.7 (0.4)	0.16 (0.02)	0.81 (0.21)	0.97 (0.22)
	587	28 (7.7)	3.7 (0.6)	0.18 (0.02)	0.81 (0.56)	0.99 (0.53)

† Total amount of P applied over the duration of the fertility experiment with yearly application in parentheses

‡ P rates applied once in 1977

*Values reported as mean of four replications with standard deviation in parentheses

Table 2.4. Runoff total phosphorus (TP) correlated to four types of soil phosphorus values in long-term fertility runoff plots

Grant Soil Series		Kirkland Soil Series		Taloka Soil Series	
	r^2		r^2		r^2
TP=0.0015M3P + 1.2	0.05	TP=0.017M3P + 0.36 *	0.66	TP=0.012M3P + 0.55	0.19
TP=0.0092WSP + 1.2	0.04	TP=0.26WSP + 0.44*	0.61	TP=0.19WSP + 0.52	0.21
TP=0.019PSI$_{OX}$ + 1.0	0.07	TP=0.18PSI$_{OX}$ - 0.28 *	0.72	TP=0.056PSI$_{OX}$ + 0.39	0.09
TP=0.081PSI$_{Smax}$ + 1.1	0.19	TP=0.68PSI$_{Smax}$ + 0.44 *	0.61	TP=0.44PSI$_{Smax}$ + 0.53	0.18

*Denotes significance (α=0.05)

†M3P - Soil Mehlich 3 P

‡WSP - Soil Water Soluble P

§PSI$_{OX}$ - Ammonium Oxalate P Saturation Index

**PSI$_{Smax}$ - P Sorption Saturation

Table 2.5. Runoff dissolved reactive phosphorus (DRP) correlated to four types of soil phosphorus values in long-term fertility runoff plots

Grant Soil Series		Kirkland Soil Series		Taloka Soil Series	
	r^2		r^2		r^2
$DRP=0.0045M3P + 0.073$ *	0.69	$DRP=0.0016M3P + 0.0057$ *	0.56	$DRP=0.0026M3P + 0.065$ *	0.59
$DRP=0.033WSP + 0.27$ *	0.69	$DRP=0.023WSP + 0.016$*	0.48	$DRP=0.039WSP + 0.065$ *	0.58
$DRP=0.046PSI_{OX} - 0.16$ *	0.50	$DRP=0.015PSI_{OX} - 0.041$ *	0.51	$DRP=0.017PSI_{OX} - 0.0030$ *	0.51
$DRP=0.058PSI_{Smax} + 0.17$ *	0.69	$DRP=0.061PSI_{Smax} + 0.065$ *	0.48	$DRP=0.089PSI_{Smax} + 0.065$ *	0.58

*Denotes significance (α=0.05)

†M3P - Soil Mehlich 3 P

‡WSP - Soil Water Soluble P

§PSI_{OX} - Ammonium Oxalate P Saturation Index

**PSI_{Smax} - P Sorption Saturation

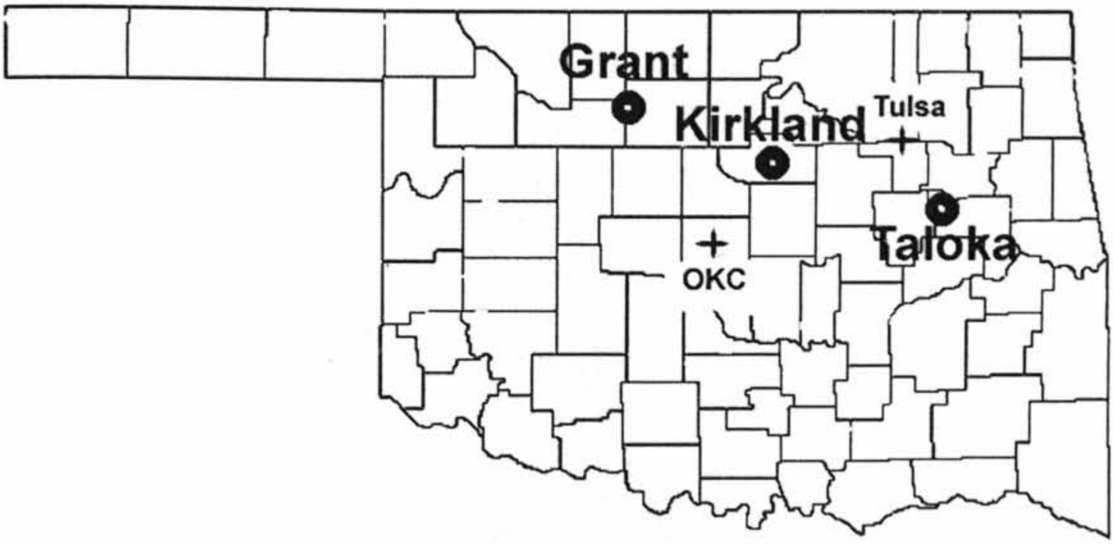

Figure 2.1. Long-term fertility research sites and soil series evaluated in runoff phosphorus study.

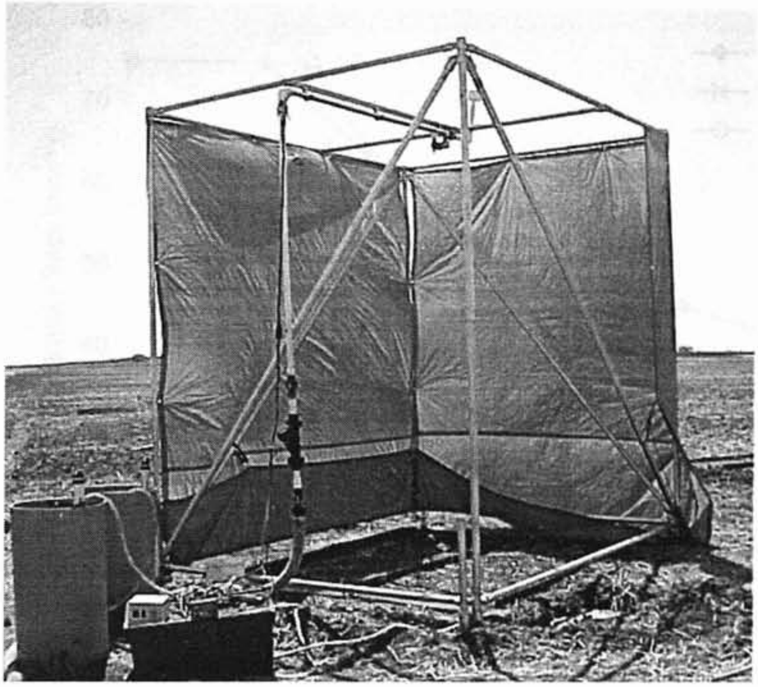

Figure 2.2. Solenoid-operated, variable intensity rainfall simulator used with paired 1m x 2m runoff plots established on long-term fertility research plots.

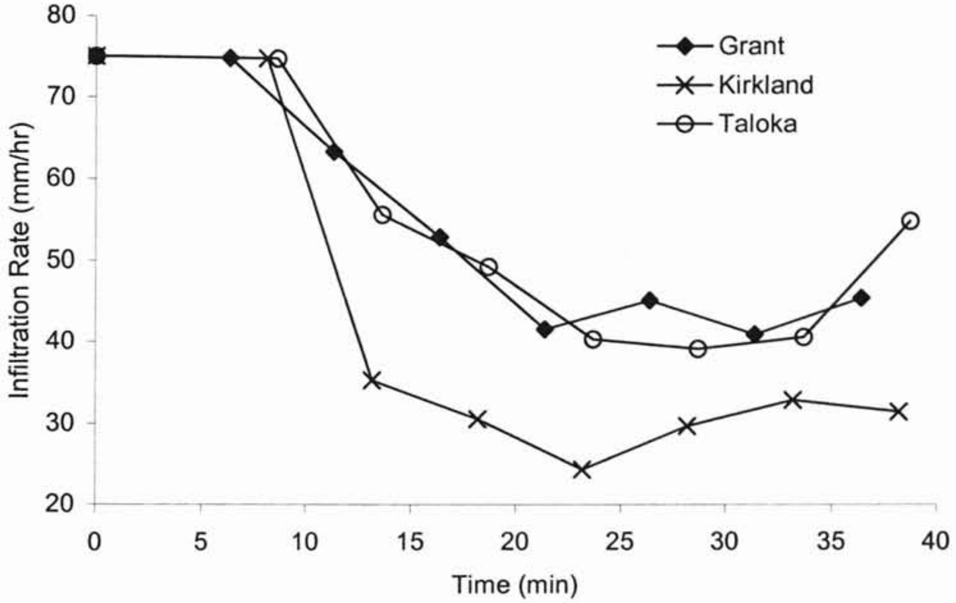

Figure 2.3. Average infiltration rate vs. time for three soils.

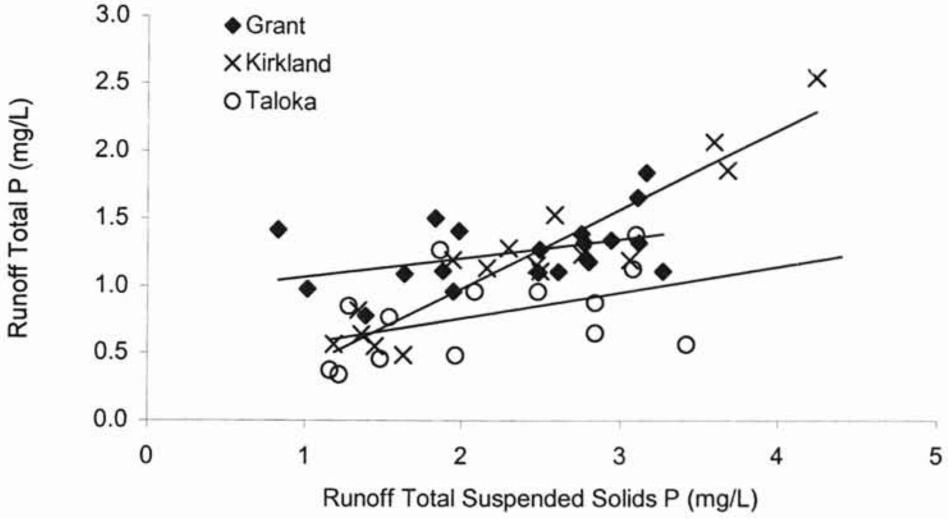

Figure 2.4. Relationship between runoff total phosphorus and runoff total suspended solids of long-term fertility research plots.

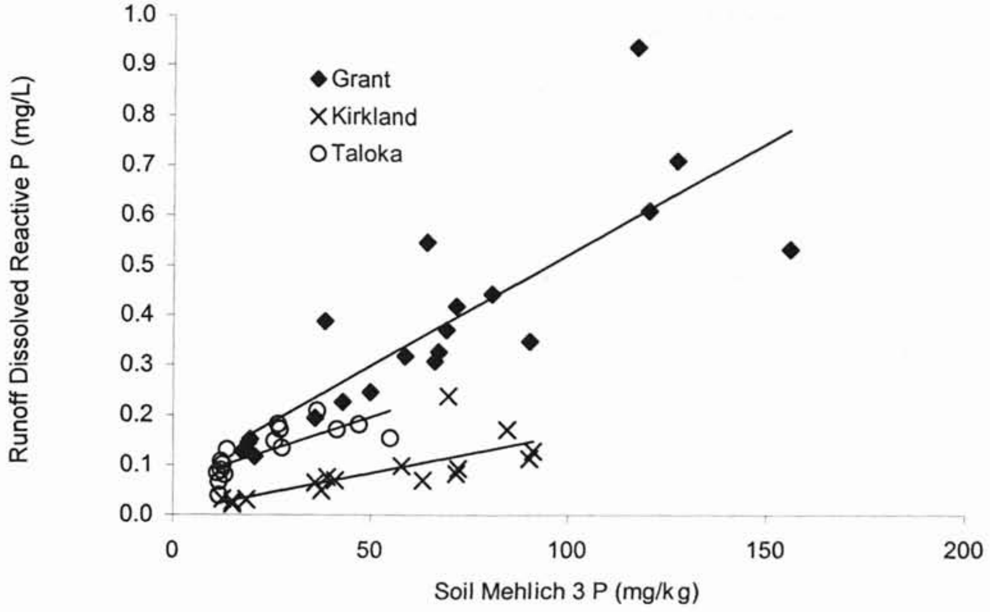

Figure 2.5. Relationship between runoff dissolved reactive phosphorus and soil Mehlich 3 phosphorus of long-term fertility research plots.

SUMMARY CONCLUSIONS AND FUTURE RESEARCH RECOMMENDATIONS

Summary Conclusions

As there is a need for more information on the relationship between runoff phosphorus (P) and soil test P, many researchers have performed runoff P studies using simulated rainfall on indoor soil micro-plots and on larger field runoff plots. It has been shown that there is a direct relationship between runoff P and soil P level using each of these methods. However, there is little information on how the results of these two experimental methods compare.

Results from the indoor (Chapter 1) and outdoor (Chapter 2) rainfall simulation studies can be compared here as environmental factors such as rainfall intensity and runoff duration were held constant throughout both of the rainfall simulation studies. In addition, each study shared a common soil to allow for soil series specific comparisons. However, the central differences between the studies were the collection and fertilizer treatment of the soils used in the rainfall simulations. For the indoor study, soils were collected and placed in runoff boxes and treated with high levels of commercial P fertilizer. In contrast, outdoor field plots were established on long-term fertility plots that annually receive relatively low rates of P application. As a result of the collection and soil processing methods used for the indoor simulation study, the infiltration rates of the repacked soils for the indoor study were much higher than those of comparable soils in the outdoor rainfall simulation study. This suggests that an indoor runoff study may not accurately simulate actual field hydrologic conditions and may be misleading.

The soil test P levels were much higher for the indoor rainfall simulation study than for the outdoor study. Consequently, the concentration of total P (TP) and dissolved reactive P (DRP) lost in runoff was consistently higher for the soils used in the indoor study when compared to the soils used in the outdoor study. However this difference was roughly proportional to the amount of soil P for that respective treatment.

In both studies, runoff DRP was highly correlated to soil P, although the relationships were stronger (higher r^2 value) in the indoor runoff study than in the outdoor study. Runoff DRP – soil P regression slopes ranged from 0.0019 to 0.0046 between the two studies. This observed difference may be a result of the P fertilizer method/rates used between the two studies. This suggests that similar approaches to amendment application method and rates should be taken to accurately compare indoor (greenhouse) and outdoor (field) studies.

The differences observed between the indoor and outdoor studies include considerable differences in the infiltration rates of the same soil series and considerable differences in the relationship between runoff DRP and soil P in the same soil series. These observed differences suggest that results of indoor and outdoor runoff simulations may not necessarily be used interchangeably. However, each experimental method has its advantages and may be well suited for different situations.

Research Recommendations

A considerable amount of interest has been focused on finding ways to reduce runoff P concentrations. Often times industrial and municipal waste products may be used to trap P out of runoff. However, there are many waste substances available, though there is little data quantifying the usefulness and possible drawbacks of using industrial and municipal wastes to reduce runoff P concentrations. Performing additional rainfall simulations on the soils used in the greenhouse study after amendment with industrial or municipal wastes may provide some useful information for future amendment use. The high levels of soil Mehlich 3 P in the soil used in the greenhouse study may provide an assessment of the capacity of waste materials to trap and absorb P from runoff. In addition, various rates, waste material types, and application methods may be tested to assess the most effective management strategy of using industrial or municipal waste amendments for the reduction of runoff P.

The field runoff study assessed the amount of runoff P lost from field soil plots in between winter wheat growing seasons. Performing rainfall simulations during different stages of winter wheat growth during the growing season may provide year-round information of runoff P losses from winter wheat agriculture. More information may also be gathered concerning P fertilizer impacts on runoff water quality by timing field rainfall simulations after annual P fertilizer applications.

APPENDIXES

Appendix A—Chapter 1 Data Compilation

Richfield Soil Series Results

Box #	Time To Runoff min	DRP mg/L	Total P mg/L	PP mg/L	DRP Load mg	Total P Load mg	Volume L	Runoff Depth mm	WSP mg/kg	M3P mg/kg	PSI_{Smax} %	PSI_{OX} %	TSS mg/L
Richfield Treatment One													
34	5	0.10	1.86	1.76	1.29	23.85	12.80	33.75	4.14	25.97	1.33	12.81	4.80
28	6	0.08	2.12	2.04	1.19	31.15	14.70	38.76	3.78	28.18	1.21	13.15	11.38
44	5	0.17	1.90	1.73	2.21	25.37	13.35	35.20	4.50	29.93	1.44	13.68	3.52
45	6	0.08	1.90	1.82	1.17	27.55	14.50	38.24	4.68	26.95	1.50	10.54	2.94
StDev	0.58	0.04	0.12	0.14	0.50	3.17	0.91	2.41	0.40	1.70	0.13	1.39	3.89
Ave	5.50	0.11	1.95	1.84	1.46	26.98	13.84	36.49	4.27	27.76	1.37	12.54	5.66
Richfield Treatment Two													
14-1	3	0.87	5.04	4.17	15.12	87.96	17.45	46.02	32.32	162.40	10.36	28.45	5.38
12-1	6	0.69	3.57	2.88	9.60	49.81	13.95	36.79	35.57	160.44	11.40	28.93	3.38
17-1	6	0.74	2.20	1.46	9.47	28.15	12.80	33.75	24.19	176.18	7.75	29.13	1.79
3-1	1	0.62	2.04	1.43	9.31	30.84	15.10	39.82	37.01	190.86	11.86	16.25	2.66
StDev	2.45	0.11	1.40	1.31	2.83	27.59	1.99	5.24	5.73	14.12	1.84	6.30	1.53
Ave	4.00	0.73	3.21	2.49	10.88	49.19	14.83	39.09	32.27	172.47	10.34	25.69	3.30
Richfield Treatment Three													
31	3	1.49	5.70	4.22	19.33	74.14	13.00	34.28	73.90	413.80	23.69	52.03	9.58
30	4	1.12	5.93	4.81	15.01	79.19	13.35	35.20	77.83	438.29	24.95	50.21	7.90
41	4	1.82	4.75	2.94	27.86	72.94	15.35	40.48	104.60	444.10	33.53	52.52	2.78
39	8	1.33	7.53	6.20	19.99	113.36	15.05	39.69	83.79	415.92	26.86	48.51	2.20
StDev	2.22	0.29	1.15	1.36	5.35	19.16	1.18	3.12	13.67	15.42	4.38	1.83	3.68
Ave	4.75	1.44	5.98	4.54	20.55	84.91	14.19	37.41	85.03	428.03	27.25	50.82	5.62
Richfield Treatment Four													
36	6	4.25	7.74	3.49	65.42	119.20	15.40	40.61	185.80	802.17	59.55	74.09	3.24
20	4	3.76	9.14	5.38	56.79	138.03	15.10	39.82	218.40	867.64	70.00	81.40	1.70
18	4	3.60	8.85	5.25	40.31	99.10	11.20	29.53	207.60	829.41	66.54	78.84	1.76
19	3	3.60	12.98	9.38	48.95	176.53	13.60	35.86	173.20	767.98	55.51	76.03	4.00
StDev	1.03	0.31	2.28	2.49	10.74	32.96	1.92	5.06	20.49	42.20	6.57	3.20	1.13
Ave	4.13	3.80	9.68	5.88	52.87	133.21	13.83	36.46	196.25	816.80	62.90	77.59	2.67

Dennis Soil Series Results

Box #	Time To Runoff min	DRP mg/L	Total P mg/L	PP mg/L	DRP Load mg	Total P Load mg	Volume L	Runoff Depth mm	WSP mg/kg	M3P mg/kg	PSI_{Smax} %	PSI_{OX} %	TSS mg/L
Dennis Treatment One													
5	7	0.15	1.00	0.85	1.41	9.28	9.25	24.39	2.87	35.16	1.52	7.75	1.50
27	2	0.13	1.10	0.97	0.45	3.89	3.55	9.36	3.06	34.53	1.62	10.60	3.10
42	2	0.09	1.50	1.41	1.29	22.08	14.75	38.90	3.24	32.53	1.71	11.19	6.40
6	7	0.10	0.47	0.37	0.48	2.27	4.80	12.66	3.42	37.00	1.81	12.01	2.20
StDev	2.89	0.03	0.42	0.43	0.51	8.98	5.07	13.37	0.23	1.84	0.12	1.85	2.17
Ave	4.50	0.12	1.02	0.90	0.91	9.38	8.09	21.33	3.15	34.80	1.66	10.39	3.30
Dennis Treatment Two													
46-1	3	0.44	2.17	1.73	6.31	31.40	14.50	38.24	19.13	137.95	10.12	21.05	2.62
23-1	2	0.43	2.88	2.45	6.78	45.89	15.95	42.06	18.05	138.97	9.55	23.20	3.41
13-1	2	0.43	2.36	1.92	5.37	29.13	12.35	32.57	16.42	148.40	8.69	24.10	2.87
22-1	10	0.29	1.53	1.23	3.21	16.64	10.90	28.74	15.70	151.28	8.31	27.25	1.15
StDev	3.86	0.07	0.56	0.50	1.58	11.99	2.24	5.91	1.55	6.69	0.82	2.57	0.97
Ave	4.25	0.40	2.23	1.83	5.42	30.76	13.43	35.40	17.33	144.15	9.17	23.90	2.51
Dennis Treatment Three													
9	7	0.68	4.35	3.67	8.57	55.03	12.65	33.36	70.29	399.93	37.19	45.38	3.50
21	8	0.67	3.62	2.95	7.41	40.00	11.05	29.14	74.22	441.80	39.27	56.03	2.06
10	5	0.89	4.83	3.94	9.94	53.82	11.15	29.40	55.62	377.39	29.43	42.14	4.72
26	7	0.66	3.44	2.78	6.58	34.36	10.00	26.37	67.00	425.45	35.45	45.93	2.24
StDev	1.26	0.11	0.65	0.56	1.46	10.23	1.09	2.88	8.01	28.34	4.24	6.01	1.24
Ave	6.75	0.72	4.06	3.33	8.12	45.80	11.21	29.57	66.78	411.14	35.33	47.37	3.13
Dennis Treatment Four													
7	11	1.45	9.80	8.35	17.53	118.57	12.10	31.91	192.60	846.47	101.90	69.04	2.88
43	5	2.07	9.73	7.66	25.88	121.58	12.50	32.96	175.40	885.17	92.80	76.74	2.42
24	1	2.10	9.74	7.64	27.23	126.16	12.95	34.15	265.40	940.98	140.42	83.58	4.02
1	6	2.07	7.90	5.83	20.39	77.79	9.85	25.97	285.20	1027.75	150.90	137.30	1.62
StDev	4.11	0.32	0.93	1.08	4.57	22.38	1.38	3.63	53.79	78.67	28.46	31.00	1.00
Ave	5.75	1.92	9.29	7.37	22.76	111.02	11.85	31.25	229.65	925.09	121.51	91.67	2.73

Kirkland Soil Series Results

Box #	Time To Runoff min	DRP mg/L	Total P mg/L	PP mg/L	DRP Load mg	Total P Load mg	Volume L	Runoff Depth mm	WSP mg/kg	M3P mg/kg	PSI_{Smax} %	PSI_{OX} %	TSS mg/L
Kirkland Treatment One													
15	9	0.16	1.57	1.41	1.99	19.72	12.55	33.09	3.24	55.12	1.33	11.07	1.80
40	2	0.13	3.18	3.05	1.73	43.57	13.70	36.13	5.22	56.82	2.14	11.71	8.42
11	8	0.13	1.92	1.80	1.92	29.23	15.20	40.08	2.33	56.16	0.96	10.70	4.82
38	2.5	0.13	2.34	2.21	1.81	33.45	14.30	37.71	5.04	56.24	2.07	11.03	7.88
StDev	3.64	0.02	0.69	0.70	0.12	9.89	1.11	2.93	1.41	0.71	0.58	0.42	3.06
Ave	5.38	0.13	2.25	2.12	1.86	31.49	13.94	36.75	3.96	56.08	1.62	11.13	5.73
Kirkland Treatment Two													
29-1	2	0.43	5.18	4.75	7.80	93.00	17.95	47.33	21.52	174.63	8.82	18.69	7.18
16-1	9	0.40	2.64	2.24	5.57	36.60	13.85	36.52	17.69	182.56	7.25	18.85	2.17
33-1	5	0.25	1.61	1.36	3.69	23.58	14.66	38.65	14.07	158.46	5.77	19.18	3.44
37-1	6	0.29	1.92	1.63	5.97	39.62	20.60	54.32	20.21	158.65	8.28	18.70	2.86
StDev	2.89	0.09	1.62	1.55	1.68	30.67	3.11	8.21	3.28	12.02	1.34	0.23	2.24
Ave	5.50	0.34	2.84	2.49	5.76	48.20	16.76	44.21	18.37	168.57	7.53	18.85	3.91
Kirkland Treatment Three													
47	6	1.68	10.71	9.03	25.99	165.47	15.45	40.74	68.73	481.59	28.17	34.04	12.58
4	3	1.16	8.70	7.55	16.02	120.52	13.85	36.52	68.44	498.49	28.05	36.81	3.48
32	4	1.03	8.45	7.42	15.87	130.49	15.45	40.74	61.21	478.24	25.09	36.05	3.86
8	7	1.82	11.85	10.03	26.63	173.60	14.65	38.63	70.29	453.69	28.81	38.54	6.08
StDev	1.83	0.39	1.63	1.25	5.99	25.96	0.77	2.02	4.05	18.48	1.66	1.87	4.21
Ave	5.00	1.42	9.93	8.51	21.13	147.52	14.85	39.16	67.17	478.00	27.53	36.36	6.50
Kirkland Treatment Four													
48	7	2.41	14.59	12.18	34.52	208.64	14.30	37.71	128.70	794.75	52.75	48.99	7.52
2	8	2.31	10.35	8.04	35.70	159.91	15.45	40.74	129.90	979.44	53.24	54.63	3.50
25	6	2.02	16.67	14.65	28.27	233.38	14.00	36.92	128.10	883.82	52.50	49.72	5.38
35	5	2.33	13.49	11.16	34.67	201.00	14.90	39.29	196.70	1016.33	80.61	55.59	6.86
StDev	1.29	0.17	2.64	2.74	3.39	30.52	0.64	1.70	33.91	99.67	13.90	3.36	1.78
Ave	6.50	2.27	13.78	11.51	33.29	200.73	14.66	38.67	145.85	918.58	59.77	52.23	5.82

Richfield 5 Minute Interval Sampling Results

Time	Box #	DRP mg/L	Total P mg/L	Volume L	PP mg/L	DRP * Load mg	Total P* Load mg	TSS mg/L	TSS* Load mg
5	14-1	1.54	6.04	2.20	4.50	3.39	13.29	1.96	4.31
10	14-2	1.06	5.89	2.60	4.83	2.76	15.31	3.04	7.90
15	14-3	0.85	5.45	3.30	4.60	2.79	17.98	6.74	22.24
20	14-4	0.73	4.53	3.10	3.80	2.26	14.05	4.48	13.89
25	14-5	0.59	4.68	3.10	4.09	1.82	14.50	5.58	17.30
30	14-6	0.67	4.07	3.15	3.40	2.11	12.83	8.94	28.16
5	12-1	1.18	4.39	1.75	3.21	2.06	7.68	3.20	5.60
10	12-2	0.87	3.69	2.35	2.82	2.05	8.68	2.38	5.59
15	12-3	0.61	3.18	2.25	2.57	1.36	7.16	1.92	4.32
20	12-4	0.55	3.52	2.40	2.97	1.31	8.45	2.84	6.82
25	12-5	0.57	3.84	2.70	3.26	1.55	10.36	4.78	12.91
30	12-6	0.51	2.99	2.50	2.49	1.27	7.49	4.74	11.85
5	17-1	1.40	3.00	0.90	1.60	1.26	2.70	2.22	2.00
10	17-2	0.91	2.74	2.25	1.83	2.05	6.17	1.78	4.01
15	17-3	0.74	2.78	2.05	2.04	1.51	5.69	1.40	2.87
20	17-4	0.66	1.86	2.35	1.20	1.56	4.38	2.06	4.84
25	17-5	0.56	1.57	2.60	1.01	1.46	4.08	1.60	4.16
30	17-6	0.62	1.94	2.65	1.32	1.64	5.13	1.88	4.98
5	3-1	0.90	2.23	2.15	1.33	1.93	4.79	2.24	4.82
10	3-2	0.82	2.45	2.00	1.63	1.64	4.90	2.08	4.16
15	3-3	0.64	1.57	2.50	0.93	1.60	3.93	2.42	6.05
20	3-4	0.50	2.23	2.50	1.73	1.26	5.57	3.12	7.80
25	3-5	0.47	2.08	3.05	1.61	1.43	6.35	2.78	8.48
30	3-6	0.50	1.83	2.90	1.32	1.46	5.30	3.04	8.82

Dennis 5 Minute Interval Sampling Results

Time	Box #	DRP mg/L	Total P mg/L	Volume L	PP mg/L	DRP * Load mg	Total P* Load mg	TSS mg/L	TSS* Load mg
5	46-1	0.77	4.75	1.95	3.98	1.51	9.27	3.90	7.60
10	46-2	0.59	2.85	2.10	2.26	1.23	5.99	4.88	10.25
15	46-3	0.42	1.32	2.90	0.90	1.21	3.81	3.48	10.09
20	46-4	0.35	2.63	2.50	2.28	0.88	6.58	2.34	5.85
25	46-5	0.28	1.32	2.35	1.03	0.66	3.09	1.76	4.14
30	46-6	0.30	0.99	2.70	0.68	0.81	2.66		
5	23-1	0.57	2.19	3.10	1.62	1.78	6.80	3.12	9.67
10	23-2	0.52	3.51	1.80	2.99	0.93	6.32	3.32	5.98
15	23-3	0.47	3.29	2.60	2.82	1.22	8.55	3.02	7.85
20	23-4	0.42	4.02	2.55	3.60	1.08	10.25	4.34	11.07
25	23-5	0.33	3.25	3.35	2.92	1.12	10.90	3.92	13.13
30	23-6	0.26	1.21	2.55	0.95	0.65	3.07	2.64	6.73
5	13-1	0.59	3.14	0.40	2.56	0.23	1.26	4.66	1.86
10	13-2	0.65	3.80	2.05	3.15	1.34	7.79	4.50	9.23
15	13-3	0.50	2.38	2.50	1.88	1.24	5.94	3.16	7.90
20	13-4	0.41	2.45	2.45	2.04	1.01	6.00	2.96	7.25
25	13-5	0.35	1.50	2.45	1.15	0.85	3.67	2.22	5.44
30	13-6	0.28	1.79	2.50	1.51	0.70	4.48	1.52	3.80
5	22-1	0.56	2.38	1.10	1.81	0.62	2.61	1.44	1.58
10	22-2	0.35	1.53	1.80	1.18	0.64	2.76	1.12	2.02
15	22-3	0.22	1.79	1.90	1.57	0.42	3.40	0.92	1.75
20	22-4	0.32	2.12	2.05	1.80	0.66	4.34	1.42	2.91
25	22-5	0.21	1.06	2.15	0.85	0.45	2.28	0.94	2.02
30	22-6	0.22	0.66	1.90	0.43	0.42	1.25	1.18	2.24

Kirkland 5 Minute Interval Sampling Results

Time	Box #	DRP mg/L	Total P mg/L	Volume L	PP mg/L	DRP * Load mg	Total P* Load mg	TSS mg/L	TSS* Load mg
5	29-1	0.72	4.06	1.15	3.33	0.83	4.67	4.84	5.57
10	29-2	0.48	7.35	3.10	6.87	1.48	22.78	7.40	22.94
15	29-3	0.37	6.22	2.55	5.84	0.95	15.85	9.74	24.84
20	29-4	0.40	5.08	3.90	4.68	1.55	19.82	8.10	31.59
25	29-5	0.41	4.50	3.55	4.09	1.44	15.96	7.46	26.48
30	29-6	0.42	3.77	3.70	3.35	1.55	13.93	4.70	17.39
5	16-1	0.48	3.21	1.35	2.73	0.64	4.33	3.06	4.13
10	16-2	0.42	2.74	2.95	2.32	1.25	8.09	1.96	5.78
15	16-3	0.41	3.73	2.25	3.32	0.93	8.39	2.32	5.22
20	16-4	0.39	2.12	5.55	1.73	2.18	11.76	1.74	9.66
25	16-5	0.33	2.30	1.75	1.97	0.57	4.03	3.02	5.29
30	16-6	--	--	--	--	--	--	--	--
5	33-1	0.31	2.12	2.20	1.81	0.68	4.66	4.24	9.33
10	33-2	0.26	2.67	3.00	2.41	0.79	8.00	3.82	11.46
15	33-3	0.26	2.56	1.65	2.30	0.42	4.22	4.18	6.90
20	33-4	0.21	1.42	2.46	1.21	0.52	3.50	2.30	5.65
25	33-5	0.22	1.28	2.50	1.05	0.56	3.20	1.74	4.35
30	33-6	0.26	2.67	2.85	2.41	0.73	7.60	4.46	12.71
5	37-1	0.43	4.86	3.55	4.43	1.53	17.26	6.44	22.86
10	37-2	0.33	1.64	3.70	1.31	1.23	6.08	3.02	11.17
15	37-3	0.25	2.08	2.85	1.83	0.71	5.94	3.18	9.06
20	37-4	0.24	1.02	3.25	0.79	0.77	3.32	1.56	5.07
25	37-5	0.25	2.19	3.20	1.94	0.80	7.01	1.30	4.16
30	37-6	0.23	1.61	4.05	1.38	0.93	6.51	1.64	6.64

Data of Mehlich 3 P Change Over 360 Days

	Nov.	Dec.	Jan	Feb	Mar	Apr	May	Jun	Aug	Oct
	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	10.0	12.0
P Added	M3P	M3P	M3P	M3P	M3P	M3P	M3P	M3P	M3P	M3P
Richfield	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
0	31.5	35.0	35.0	26.0	25.5	34.0	32.5	27.8	23.0	24.2
235	285.0	255.0	235.0	228.0	156.0	185.9	183.9	172.5	187.4	184.2
635	670.0	650.0	635.0	681.5	443.0	452.9	440.8	428.0	417.6	409.7
1135	1295.0	1105.0	1195.0	1324.5	830.5	925.3	920.3	816.8	817.4	758.7
Avg	570.4	511.3	525.0	565.0	363.8	399.5	394.3	361.3	361.3	344.2
% Change		10.4	-2.7	-7.6	35.6	-9.8	1.3	8.4	0.0	4.7
Dennis										
0	35.0	36.0	35.0	30.0	32.0	36.0	36.3	34.8	31.6	31.5
225	185.0	170.0	155.0	133.5	127.5	141.6	138.8	144.2	148.3	140.2
625	545.0	535.0	535.0	606.0	450.5	432.5	433.3	411.1	385.5	383.2
1125	970.0	935.0	1030.0	1191.5	764.5	827.0	842.0	925.1	774.0	739.0
Avg	433.8	419.0	438.8	490.3	343.6	359.3	362.6	378.8	334.8	323.5
% Change		3.4	-4.7	-11.7	29.9	-4.6	-0.9	-4.5	11.6	3.4
Kirkland										
0	57.5	64.0	63.5	57.0	53.5	52.8	52.0	56.1	59.4	58.2
180	210.0	205.0	190.0	191.5	163.5	170.1	166.3	168.6	184.7	175.8
580	580.0	540.0	540.0	530.0	450.5	473.5	467.3	478.0	449.0	447.2
1080	1045.0	920.0	980.0	872.0	764.5	909.9	906.0	918.6	846.8	874.9
Avg	473.1	432.3	443.4	412.6	358.0	401.6	397.9	405.3	385.0	389.0
% Change		8.6	-2.6	6.9	13.2	-12.2	0.9	-1.9	5.0	-1.1

Appendix B—Chapter 2 Data Compilation

Grant Soil Series Results from Field Study Performed at Lahoma, OK

P Rate kg/ha	DRP mg/L	Total P mg/L	Total P Load mg	Particulate P mg/L	M3P mg/kg	WSP mg/kg	PSI$_{OX}$ %	PSI$_{Smax}$ %	TSS g/L
638 (22)	0.31	0.97	31.37	0.66	66.50	5.90	12.85	3.37	28.74
639 (22)	0.37	1.34	44.56	0.97	69.50	5.50	12.61	3.14	29.26
640 (22)	0.33	1.29	43.93	0.96	67.50	5.70	13.38	3.26	29.24
641 (22)	0.32	1.12	25.76	0.80	59.00	4.20	12.11	2.40	25.44
ave.	0.33	1.18	36.40	0.85	65.63	5.33	12.74	3.26	28.17
Stan Dev	0.03	0.17	9.34	0.15	4.59	0.77	0.53	0.44	1.93
0	0.12	1.10	35.67	0.98	20.50	1.00	7.02	0.57	10.24
0	0.14	1.36	43.93	1.21	19.00	1.00	6.98	0.57	9.79
0	0.13	1.12	32.44	0.99	17.50	0.90	7.09	0.51	9.38
0	0.15	1.20	36.63	1.04	19.50	0.90	7.71	0.51	10.30
ave.	0.14	1.19	37.17	1.06	19.13	0.95	7.20	0.55	9.93
Stan Dev	0.02	0.12	4.85	0.11	1.25	0.06	0.34	0.03	0.57
290 (10)	0.23	0.79	34.83	0.56	43.00	3.50	9.04	2.00	18.85
291 (10)	0.25	1.12	31.56	0.88	50.00	3.50	10.57	2.00	21.72
292 (10)	0.39	1.22	56.32	0.83	38.50	2.00	9.86	1.14	17.33
293 (10)	0.20	1.40	31.00	1.21	36.00	2.10	9.14	1.20	16.32
ave.	0.27	1.13	38.43	0.87	41.88	2.78	9.65	1.71	18.55
Stan Dev	0.09	0.26	12.04	0.27	6.14	0.84	0.71	0.48	2.50
841 (29)	0.42	1.86	66.62	1.44	72.00	6.50	12.61	3.71	30.38
842 (29)	0.55	1.11	24.60	0.56	64.50	5.40	12.98	3.09	27.92
843 (29)	0.35	1.68	19.75	1.32	90.50	8.80	13.88	5.03	37.41
844 (29)	0.45	1.43	38.80	0.98	81.00	6.10	13.73	3.49	33.41
ave.	0.44	1.52	37.44	1.08	77.00	6.70	13.30	3.94	32.28
Stan Dev	0.08	0.32	21.06	0.39	11.25	1.47	0.61	0.84	4.18
1160 (40)	0.72	1.42	42.40	0.71	127.50	15.20	14.61	8.69	50.99
1161 (40)	0.95	1.34	27.31	0.39	117.50	14.20	12.56	8.11	46.43
1162 (40)	0.54	0.99	31.88	0.45	156.00	18.90	18.19	10.80	62.84
1163 (40)	0.62	1.52	41.33	0.90	120.50	14.70	18.09	8.40	50.80
ave.	0.70	1.32	35.73	0.61	130.38	15.75	15.86	9.20	52.76
Stan Dev	0.18	0.23	7.34	0.24	17.59	2.14	2.76	1.22	7.47

Kirkland Soil Series Results from Field Study Performed at Stillwater, OK

P Rate kg/ha	DRP mg/L	Total P mg/L	Total P Load mg	Particulate P mg/L	M3P mg/kg	WSP mg/kg	PSI_{OX} %	PSI_{Smax} %	TSS g/L
930 (30)	0.80	1.21	44.32	1.14	63.50	3.70	8.88	1.41	1.94
931 (30)	0.80	1.21	55.77	1.11	58.00	3.30	8.11	1.25	3.06
932 (30)	1.60	1.17	50.96	0.93	70.00	4.10	9.67	1.56	2.47
933 (30)	1.40	0.83	40.19	0.74	72.00	4.30	9.63	1.63	1.34
ave.	1.15	1.10	47.81	0.98	65.88	3.85	9.07	1.46	2.20
Stan Dev	0.41	0.19	6.91	0.18	6.38	0.44	0.74	0.17	0.73
465 (15)	0.06	1.15	69.64	1.08	41.00	2.40	7.38	0.91	2.16
466 (15)	0.07	1.30	66.55	1.22	39.00	2.50	7.31	0.95	2.30
467 (15)	0.04	1.25	60.87	1.20	37.50	2.20	7.25	0.84	2.76
468 (15)	0.05	1.13	75.00	1.06	36.00	2.00	6.49	0.76	2.50
ave.	0.06	1.21	68.01	1.14	38.38	2.28	7.11	0.87	2.43
Stan Dev	0.01	0.08	5.90	0.08	2.14	0.22	0.42	0.08	0.26
1364 (44)	0.17	1.54	101.47	1.43	90.50	6.20	12.25	2.36	2.59
1365 (44)	0.23	2.58	127.75	2.45	91.50	6.30	12.31	2.40	4.24
1366 (44)	0.04	1.88	114.95	1.79	72.50	3.40	11.12	1.29	3.68
1367 (44)	0.16	2.09	91.12	1.92	85.00	4.40	11.96	1.67	3.60
ave.	0.15	2.02	108.82	1.90	84.88	5.08	11.91	1.93	3.53
Stan Dev	0.08	0.43	15.95	0.42	8.73	1.42	0.55	0.54	0.69
0	0.05	0.57	25.65	0.54	18.50	1.20	6.70	0.46	1.19
0	0.03	0.65	27.56	0.62	15.00	1.00	4.75	0.38	1.36
0	0.03	0.56	31.29	0.53	15.00	0.80	4.53	0.30	1.45
0	0.04	0.49	13.32	0.46	12.50	0.80	4.15	0.30	1.63
ave.	0.04	0.56	24.45	0.54	15.25	0.95	5.03	0.36	1.41
Stan Dev	0.01	0.06	7.78	0.07	2.47	0.19	1.14	0.07	0.18

Taloka Soil Series Results from Field Study Performed at Haskell, OK

P Rate kg/ha	DRP mg/L	Total P mg/L	Total P Load mg	Particulate P mg/L	M3P mg/kg	WSP mg/kg	PSI$_{OX}$ %	PSI$_{Smax}$ %	TSS g/L
117	0.09	0.49	20.46	0.38	12.00	0.79	7.04	0.35	1.96
117	0.11	0.66	24.76	0.56	12.50	1.15	6.13	0.51	2.84
117	0.13	0.35	3.50	0.22	13.50	0.79	6.15	0.35	1.22
117	0.13	0.38	5.40	0.30	13.00	0.97	6.40	0.43	1.16
ave.	0.12	0.47	13.53	0.36	12.75	0.93	6.43	0.41	1.79
Stan Dev	0.02	0.14	10.66	0.15	0.65	0.17	0.42	0.08	0.79
0	0.07	0.97	20.63	0.89	11.00	0.79	5.56	0.35	2.48
0	0.06	1.14	49.69	1.10	11.50	0.61	6.40	0.27	3.08
0	0.12	0.46	18.87	0.37	12.00	0.61	5.96	0.27	1.48
0	0.08	0.89	30.98	0.82	11.50	0.79	5.51	0.35	2.84
ave.	0.08	0.87	30.04	0.80	11.50	0.70	5.86	0.31	2.47
Stan Dev	0.03	0.29	14.15	0.31	0.41	0.10	0.42	0.05	0.70
293	0.18	0.77	21.71	0.60	27.00	1.86	8.33	0.35	1.54
293	0.17	1.28	40.46	1.10	26.50	1.69	8.02	0.27	1.86
293	0.19	0.86	28.52	0.72	27.50	2.04	8.66	0.27	1.28
293	0.13	0.97	17.29	0.82	25.50	2.22	7.13	0.35	2.08
ave.	0.17	0.97	27.00	0.81	26.63	1.95	8.04	0.31	1.69
Stan Dev	0.03	0.22	10.09	0.21	0.85	0.23	0.66	0.05	0.35
587	0.17	0.57	18.10	0.40	41.50	2.40	11.15	0.82	3.42
587	0.16	--	--	--	36.50	2.58	10.58	0.74	4.04
587	0.19	1.40	33.27	1.22	47.00	2.94	8.03	0.90	3.10
587	0.15	--	--	--	55.00	3.83	12.32	0.98	4.40
ave.	0.17	0.99	25.69	0.81	45.00	2.94	10.52	0.86	3.74
Stan Dev	0.02	0.58	10.72	0.58	7.93	0.64	1.81	0.10	0.59

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VITA

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