Phosphorus Runoff from Sugarbeet Production Systems as Affected by Tillage and Phosphorus Fertilizer Placement

Matthew D. Ruark[1], John A. Lamb[2], and George W. Rehm[2]

[1]Purdue University, Department of Agronomy, Lilly Hall of Life Sciences, 915 W. State Street, West Lafayette, IN 47907-2054; [2]University of Minnesota, Department of Soil, Water, and Climate, Borlaug Hall, 1991 Upper Buford Circle, St. Paul, MN 55108.

ABSTRACT

Sugarbeet production systems are potentially vulnerable to significant phosphorus (P) losses. Production practices that may reduce P loss risk are being considered. However, the potential benefits of these practices are not well established. A rainfall simulation study was conducted to determine P losses from various tillage (moldboard, chisel, and deep chisel) and phosphorus fertilizer placement (broadcast and band). Sugarbeet (*Beta vulgaris* L.) corn (*Zea mays* L.), and soybean (*Glycine max* L.) rotations were studied. A rainfall simulator was used to create runoff events at a rainfall intensity of 5.5 cm hr^{-1}. Surface runoff was collected and analyzed for dissolved P (DP) and total P (TP). Flow-weighted P concentration (mg L^{-1}) in runoff and P loss (kg ha^{-1}) from runoff were calculated for both DP and TP. Runoff flow rate and sediment loss were also measured. Analysis of variance indicated that neither tillage nor P fertilizer placement treatments affected flow-weighted P concentration or P content loss. Also, there was no apparent difference between sugarbeet and corn-soybean production systems on P loss. Regression analysis was conducted to determine which source and/or transport factors influenced P loss. Phosphorus concentration models were heavily influenced by soil test phosphorus (STP) levels, while P content loss models were more influenced by transport factors such as runoff or sediment loss. Futher

reduction of tillage or the establishment of a dense cover crop are management practices that need to be more fully explored in sugarbeet production systems. Adopting a nutrient management plan to reduce high STP levels may reduce short-term available DP loss from sugarbeet fields.

Additional key words: *Beta vulgaris* L., eutrophication, Olsen soil test, rainfall simulator, dissolved phosphorus

In the past couple of decades the relationship between phosphorus (P) management and environmental P contamination has received increased attention. Many soils in agricultural production areas have elevated levels of soil test phosphorus (STP). Phosphorus can leave cultivated fields in a dissolved form in runoff (dissolved P, DP) or as an adsorbed form on eroded soil particles (particulate P, PP). Total phosphorus (TP) is the sum of DP and PP. Phosphorus can then enter freshwater streams, rivers, and lakes and accelerate eutrophication. Particulate P represents a long-term source of P for algae growth with a variable amount (10-90%) being immediately available (Dorich *et al.*, 1980; Sharpley *et al.*, 1992). In contrast, DP (soluble forms of orthophosphate) is immediately available for biotic uptake and therefore considered a short-term source. Since P is generally the limiting nutrient for algae and plant growth in freshwater systems, a population explosion of these organisms occurs (Sharpley *et al.*, 1994). The United States Environmental Protection Agency (USEPA) has identified eutrophication as the main cause of impaired fresh surface water quality (USEPA, 1996).

Substantial research activity has focused on P runoff. Phosphorus runoff studies have been conducted with cropping systems that include corn-soybean rotations in Iowa (Laflen and Tabatabai, 1984), wheat-fallow rotations in Texas (Sharpley, 1995), and sorghum-soybean rotations in Eastern Kansas (Kimmel *et al.*, 2001). There is little information available on how P in runoff is affected by sugarbeet production systems. The small size of the sugarbeet seed and the shallow depth of planting create the need for sugarbeet production fields to have little crop residue from the previous crop at planting. This leaves the field more susceptible to soil erosion and subsequent P losses. An understanding of the impact of varying tillage practices and P fertilizer placement on P loss would lead to better P management on sugarbeet production fields.

The effects of tillage on P losses have varied throughout the reported literature. Previous research has determined that reduced tillage systems in corn-corn and corn-soybean rotations increase the concentration of DP in surface runoff, while TP content losses were reduced (Barisas *et al.*, 1978; McDowell and McGregor, 1984). Conservation tillage reduces soil loss due to erosion by almost 50% and decrease DP concentration in runoff by 50 to 70% (Gaynor and Findlay, 1995; Andraski *et al.*, 1985). Dissolved P concentrations are greater from conservation tillage systems because of the associated method of surface application of P fertilizers, leaching of P from decomposing plant material, and the lack of sorbing material being eroded (McDowell and McGregor, 1984).

Crop residue management is inherently tied to tillage and crop rotation. Conventional tillage will generally have less surface crop residue than conservation tillage. Barisas *et al.* (1978) found as residue cover increased, DP concentration in runoff increased while TP content and sediment loss decreased. Baker and Laflen (1982) determined that residue on the soil surface can reduce nutrient losses up to 80%. Mostaghimi *et al.* (1988) found that increasing residue (from bare soil conditions) decreased DP concentrations in runoff. However, further increases in residue eventually increased DP concentrations. On clay soil with high infiltration rates, residue cover will control erosion and not considerably increase DP levels in runoff (Potter *et al.*, 1995).

Another important factor of P loss that interacts with tillage is fertilizer application. Applying P fertilizer to a field increases the concentration of DP in runoff (Baker and Laflen, 1982; Romkens and Nelson, 1974). The method of P fertilizer application can also effect P losses. Baker and Laflen (1982) found surface applied fertilizer greatly increased P concentrations in runoff compared to a 5 cm point injected fertilizer. Kimmel *et al.* (2001) found greater DP loss from broadcast applications compared to knifed application methods in no-till and ridge-till systems, but there was no difference in DP loss between applications in chisel-till systems. McIssac *et al.* (1995) found that moldboard plowing after surface application of fertilizer was the only fertilizer application and placement method that reduced DP concentration in runoff below 0.05 mg L^{-1}, leading to the conclusion that surface application of fertilizer in a no-till tillage system is likely to be problematic.

There has been some speculation that STP can be a good indicator of DP concentration in runoff. Pote *et al.* (1996) and Pote *et al.* (1999) reported evidence of a linear relationship between STP levels and DP concentrations in runoff on ultisols over a range of textures and slope. The relationship between STP and DP concentrations in runoff will vary depending on soil type and management (Sharpley *et al.*, 1996). Sharpley *et al.* (1996) concluded that climatic, topographic, and agronomic factors play a larger role in P concentrations in runoff than

STP and suggested that STP was not a reliable indicator of P loss.

Phosphorus fertilizer has been documented to increase sugarbeet root yields in soils with low STP while not affecting quality (Sims and Smith, 2001). Phosphorus fertilizer recommendations for sugarbeet are based on STP levels from soil depths of 0 to 15 or 20 cm. The P soil test is an index that has been correlated to the crop response to P fertilizers (Lamb *et al.*, 2001). Lee and Deutch (1999) found that between 1988 and 1999, there was no significant increase in STP levels from sugarbeet fields in west central Minnesota. This suggests environmental impacts from sugarbeet production are less related to fertilizer management and more closely related to tillage and residue management than to erosion and runoff.

The objectives of this study were to determine the effects of crop management operations in sugarbeet production systems on P loss, runoff flow rate, and sediment loss, to compare P losses from sugarbeet rotations with a conservation corn/soybean rotation, and to quantify factors that control P losses on a typical sugarbeet production site in south central Minnesota.

MATERIALS AND METHODS

The experimental site was located in Chippewa County, Minnesota on a Colvin Spicer silty clay loam (fine-silty, mixed, superactive, frigid Typic Calciaquoll and fine-silty, mixed, superactive, calcareous, mesic Typic Endoaquoll) complex with an average slope of 1.87% (range 0.63 – 2.82%) and an average pH of 7.9 (range 7.7 – 8.1). A randomized complete block, split plot experimental design was established. The whole plot treatments were crop management systems of varying crop rotations and tillage operations (Table 1). The split plot treatments were P fertilizer application methods (broadcast or band applied to a depth of 12.7 cm). Both P fertilizer application methods applied 0-44-0 triple super phosphate at a rate of 20 kg-P ha^{-1}, as per University of Minnesota recommendations. Primary tillage operations were conducted in the fall and fertilizer application and subsequent secondary tillage operations occurred in the spring prior to planting. All crops were planted in 56 cm row spacings. The plots were established on artificially drained soils, although the exact orientation of the tiles were unknown.

One runoff event was generated per treatment plot in the summer of 2001. A portable rainfall simulator (Edwards *et al.*, 1992) located 3 m above the soil surface applied a rainfall intensity of 5.5 cm hr^{-1}. Prior to rainfall simulation, runoff catchment areas (1.1 m^2) were created by overlapping corrugated sheet metal around the catchment area.

Table 1. Description of tillage/crop rotation and phosphorus fertilizer application treatments.

Crop Rotation[†]	**Tillage**
Soybean/Corn	Moldboard previous to soybean
Corn/Soybean	Chisel previous to corn
Sugarbeet/Soybean/Corn	Moldboard previous to sugarbeet
Sugarbeet/Soybean/Corn	DMI previous to sugarbeet
Sugarbeet/Soybean/Corn	DMI previous to sugarbeet, spring oat cover crop
Fertilizer Application	**Fertilizer Application Rate**
Broadcast application spring incorporated	20 kg ha^{-1}
Band application depth of 12.7 cm spacing of 56 cm	20 kg ha^{-1}

[†] Crop listed first indicates crop on which rainfall simulation occurred

Metal catchment trays were placed on the downslope edge of the catchment area to collect runoff and sediment. Runoff was collected over a 60-minute period beginning at the onset of runoff. Runoff flow rates were determined by collecting 30 to 60 second samples of runoff water every 5 minutes starting 2.5 minutes after initiation of runoff. Duplicate samples were collected for DP and TP concentration at time 3, 8, 13, 18, 23, 30, 40, and 55 minutes. Water samples for DP and TP analysis were placed on ice and in the dark until they were analyzed. Dissolved P was analyzed colormetrically on decanted samples using the method outlined by Murphy and Riley (1962). Total P was analyzed by the same method, after aggressively mixing the sample and digesting it with sulfuric acid and mercuric acid (Olsen and Sommers, 1982). Particulate P was calculated as the difference between TP and DP. Phosphorus content loss (kg ha^{-1}) was calculated by multiplying P concentration by the appropriate proportion of hourly flow and summed. Phosphorus concentrations (mg L^{-1}) were calculated and reported as flow-weighted, hourly concentrations. Runoff samples were dried and weighed for sediment content. Total sediment loss was calculated in the same manner as P content loss.

Soil samples were taken prior to simulated rainfall and analyzed for soil test P and antecedent soil moisture. Soil test P was determined using the Olsen-P soil test (Frank *et al.*, 1997) on soil to a depth of 2.5 cm. Soil moisture samples (to a depth of 15 cm) were taken

Table 2. ANOVA table for phosphorus loss values (NS = not significant at α=0.05).

	Content Loss kg ha-1			Concentration mg L-1		
Treatment	**DP**	**PP**	**TP**	**DP**	**PP**	**TP**
	---------------- P-value ----------------					
Crop Management (CM)	NS	NS	NS	NS	NS	NS
P fertilizer application (PFA)	NS	NS	NS	NS	NS	NS
CM x PFA	NS	NS	NS	NS	NS	NS
CV (%)	41.5	49.2	46.2	9.4	37.6	31.4

Table 3. Mean, minimum, and maximum values of measured variables.

Variable	Unit	Mean	Minimum	Maximum
DP concentration	mg L^{-1}	0.96	0.47	1.78
PP concentration	mg L^{-1}	4.32	1.08	10.63
TP concentration	mg L^{-1}	5.28	1.87	12.40
DP content loss	kg ha^{-1}	0.16	0.06	0.32
PP content loss	kg ha^{-1}	0.73	0.22	1.73
TP content loss	kg ha^{-1}	0.89	0.29	1.96
Runoff flow rate	L hr^{-1}	23.0	9.09	67.8
Sediment loss	Mg ha^{-1}	0.68	0.13	3.86
Olsen-P soil test	mg kg-1	40	9	109
Residue	%	8.5	3.0	15.0
Crr[†]	--	1.7	1.1	3.1
Cpr[‡]	--	4.8	2.4	8.3
SOM[§]	%	7.43	6.00	8.30

[†] surface roughness parallel to row

[‡] surface roughness perpendicular to row

[§] soil organic matter (0 - 2.5 cm depth)

immediately before rainfall simulation, dried at 105°C, and reported as g kg^{-1}. Soil physical properties linked to P loss were measured and included residue cover and surface roughness. The line intersect method (Laflen *et al.*, 1981) was used to determine residue cover and the chain method (Saleh, 1993) was used to determine surface roughness in the direction of the row (Crr) and perpendicular to the row (Cpr). The slope of each plot was measured as the difference of elevation using a GPS unit by Ashtech™. Statistical analysis was conducted using SAS (SAS Inst., 1996).

RESULTS

Analysis of variance

Phosphorus losses were calculated as both content loss (kg ha^{-1}) and hourly, flow-weighted concentration (mg L^{-1}) in the first 60 minutes of runoff. Analysis of variance indicated that there were no significant differences between crop management systems, P fertilizer application methods, or their interaction for DP, PP, or TP content loss (Table 2). Additionally, DP, PP, and TP concentrations in runoff did not differ significantly among any of the experimental treatments (Table 2). Mean values and value ranges of P losses are summarized in Table 3.

When comparing different primary tillage systems with respect to P loss, we would expect that conservation tillage practices (chisel and DMI chisel) would result in less P content loss than a conventional tillage practice (moldboard plow) as a result of a reduction in runoff flow rate and soil erosion loss. It has generally been shown that conservation tillage practices reduce total P loss from a field, but increased DP concentration in runoff (Romkens and Nelson, 1974; Barisas *et al.*, 1978; McDowell and McGregor, 1984; Gaynor and Findlay, 1995). With respect to crop rotation, our results were similar to those found by Laflen and Tabatabi (1984) who found no differences in P loss between corn and soybean fields. There was no measurable effect of oat cover crop on P loss, however cover crop was only used with DMI chisel. Additionally, visual inspection of oat cover crop at time of rainfall simulation suggested that the oat cover crop was not developed enough to reduce runoff or sediment loss. Our results did not reflect any practical differences in P content loss or P concentration in runoff from any crop management system.

Surface applied P fertilizer has been shown to increase DP concentrations in runoff (Baker and Laflen, 1982). However, McIssac *et al.* (1995) reported a reduction in DP concentration in runoff when surface applied P fertilizer was incorporated with a moldboard plow. Our results were more consistent with Kimmel *et al.* (2001) who concluded that DP losses were not significantly different between broadcast and knife injected fertilizer application in chisel-till systems and Hansen *et al.* (2001) who found no effects of P placement on P concentration in runoff from chisel plowed systems.

Runoff flow rate and sediment loss means and value ranges over all treatments are summarized in Table 3. There were no significant differences in runoff flow rate among the different crop management systems or the P fertilizer application treatments (Table 4). Analysis of variance reported an interaction between the two factors, but this effect

Table 4. ANOVA table for runoff flow rate, sediment loss, and soil surface measurements (Residue, Crr, and Cpr only measured at whole plot level; NS = not significant at α=0.05, * indicates significance at α=0.05, ** indicates significance at α=0.01).

Treatment	Runoff L hr^{-1}	Sediment Mg ha^{-1}	Residue %	Crr† roughness value	Cpr‡ roughness value
	P-values				
Crop Management (CM)	NS	NS	**	*	**
P fertilizer application (PFA)	NS	NS	--	--	--
CM x PFA	*	NS	--	--	--
CV (%)	30.8	126	9.5	20.7	10.0

† surface roughness parallel to row
‡ surface roughness perpendicular to row

is skewed by one large runoff event that was double that of any other event. Sediment losses were not significantly affected by crop management, P fertilizer application, or their interaction (Table 4). According to the Soil Survey of Chippewa County, Minnesota (Brug, 1982), the tolerable amount of erosion loss (T) for the Colvin and Spicer series is 11.2 Mg ha^{-1} yr^{-1}. Even the largest sediment loss event was well below T from this 1-hr, 50-year storm event (Huff and Angel, 1992). It can be concluded that the hourly sediment losses in this study (0.29 – 1.96 kg ha^{-1}) comprised only a small fraction of the yearly tolerable soil loss.

Residue cover and surface roughness measurements were taken on the whole plot level (crop management practice) after planting and were statistically analyzed accordingly (Table 3, Table 4). Measured residue cover was greatest in sugarbeet plots with DMI (12.9%) and DMI with cover crop (10.8%) and was least in soybean plots with chisel plow (4.3%). Sugarbeet with moldboard plow after corn had greater residue cover than soybean with moldboard plow after corn (9.4% and 4.8% respectively). The residue cover values were low and inconsistent with what was expected under the different tillage systems. The Natural Resource Conservation Service defines conservation tillage as tillage systems leaving more than 30% of the surface covered with residue. According to this definition, chisel and DMI tillage systems used in this study would not be considered conservation tillage. Secondary tillage and other necessary management operations likely depleted residue amounts and confounded any effect of tillage and crop rotation.

Surface roughness parallel to the row (Crr) and perpendicular to the row (Cpr) was significantly affected by crop management system (Table 4). However, the results were inconclusive and unexpected, as the two comparable DMI tillage treatments were significantly different from each other (data not shown). Also, the chisel plow before corn treatment had the smallest Cpr value, where we would expect the chisel plow to have a larger value caused by formation of ridges.

The Crr and Cpr factors relate closely to a category of "almost flat" (Saleh, 1993). This indicates that any ridges created by chisel and DMI chisel plows were reduced by the secondary tillage and planting operations used in this study and commonly used in sugarbeet production systems. The lack of residue cover appeared to have been influenced by the same management practices.

Multiple regression analysis

Analysis of variance did not provide any conclusive evidence of an effect of tillage/crop rotation treatments and P fertilizer application treatments on P concentrations and P content losses. Multiple regression analysis was performed to determine which variables contributed most to P loss. Six regression models were constructed, one for each of the following dependent (Y) variables: DP, PP, and TP concentration and DP, PP, and TP content loss. Variables included in the following correlation and regression analysis were: runoff flow rate (RO), total sediment loss (SED), residue cover (RES), surface roughness with row (Crr), surface roughness perpendicular to row (Cpr), Olsen-P soil test (OP), soil moisture (SM), and soil organic matter (SOM). Correlation coefficients between P loss and measured variables are summarized in Table 5.

Criteria for variables to be included in the regression model were the strength of correlation and lack of intercorrelation. Other criteria for the regression models were that at least one source (OP) or transport factor (RO or SED) was to be included in each model and that no more than three terms were to be included. Several models for each dependent variable were calculated to determine a maximum R^2, which is an indicator of the goodness of fit of the regression model. The regression models calculated were specific to the soil type, landscape, and rainfall runoff period as described for this experiment. All six regression models are listed in Table 6 along with regression coefficients.

The model for DP concentration only included the source variable OP and suggested that as the amount of labile P in the upper 2.5 cm of soil increased, the DP concentration in runoff increased slightly (Table 6, Figure 1). The OP value was expected to have a large impact on the DP concentration in runoff as it is a main factor in many P index-

Table 5. Correlation coefficients (r) of phosphorus losses to measured variables (NS = not significant at α=0.05, * significant at α=0.05, ** significant at α=0.01).

	Concentration, mg L^{-1}						Content Loss, kg ha^{-1}					
Variable	**DP**		**PP**		**TP**		**DP**		**PP**		**TP**	
Olsen-P soil test	0.78	**	0.51	*	0.58	**	0.07	NS	-0.10	NS	-0.08	NS
Runoff	-0.45	*	-0.33	NS	-0.37	NS	0.66	**	0.52	*	0.57	**
Sediment	-0.02	NS	0.40	NS	0.35	NS	0.45	*	0.84	**	0.82	**
Soil Moisture	0.66	**	0.36	NS	0.43	*	0.48	*	0.18	NS	0.24	NS
Residue	0.30	NS	0.03	NS	0.07	NS	-0.26	NS	-0.47	*	-0.46	*
Crr†	0.64	**	0.32	NS	0.39	NS	0.08	NS	-0.11	NS	-0.09	NS
Cpr‡	0.47	*	0.34	NS	0.38	NS	0.23	NS	0.08	NS	0.10	NS
SOM§	0.71	**	0.25	NS	0.35	NS	0.15	NS	-0.25	NS	-0.20	NS

† surface roughness parallel to row

‡ surface roughness perpendicular to row

§ soil organic matter (0 - 2.5 cm depth)

Table 6. Regression models and statistics for phosphorus loss.

Dependent Variable	Regression Model	R^2
DP concentration	Y = 0.59 + 0.0092 (OP[†])	0.61
PP concentration	Y = 3.08 + 0.015 (OP) + 0.54 (SED[‡]) + 0.056 (OP*SED)	0.74
TP concentration	Y = 2.53 + 0.0073 (OP) + 0.50 (SED) + 0.054 (OP*SED)	0.73
DP content loss	Y = -0.40 + 0.0038 (RO[§]) + 0.0013 (SM[¶])	0.74
PP content loss	Y = 0.29 + 0.008 (RO) + 0.37 (SED)	0.77
TP content loss	Y = 0.37 + 0.011 (RO) + 0.39 (SED)	0.76

[†] Olsen-P soil test (0 - 2.5 cm)
[‡] Sediment loss
[§] Runoff flow rate
[¶] Soil moisture

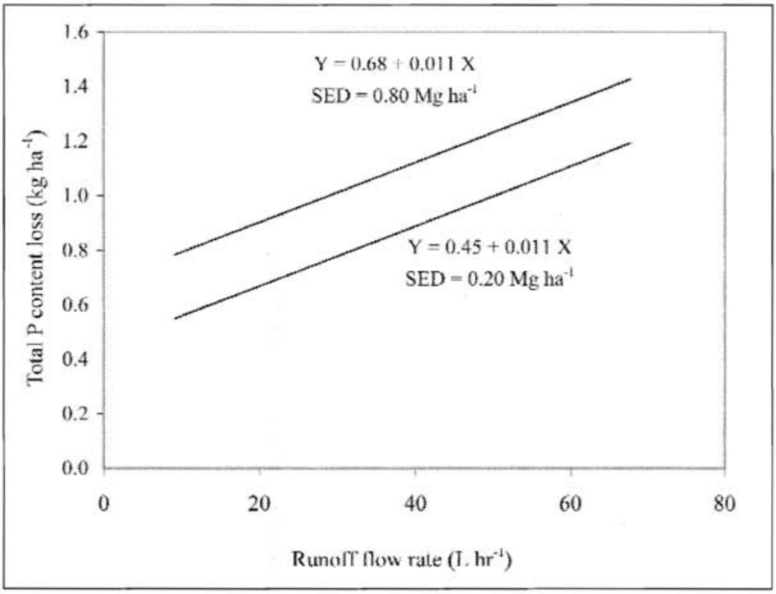

Fig. 1. Response of dissolved phosphorus concentration to Olsen P soil test.

es (Lemunyon and Gilbert, 1993; Grubek *et al.*, 2000).

The regression models for PP and TP concentration included several strongly correlated independent variables. Again, the source factor OP correlated strongly with concentration. In addition to OP, the best model for PP and TP concentration included sediment (SED) and the interaction of OP and SED (Table 6). To illustrate the relationship between OP and SED on PP and TP concentration, three OP levels were selected: 16 (low), 30 (medium), and 91 (high) mg kg^{-1}. These OP levels were calculated into the regression model to graph sediment versus P concentration (Figure 2 and Figure 3). Figures 2 and 3 indicate that as OP increased, PP and TP concentration increased at a greater rate with increasing sediment levels. The PP and TP concentration in runoff were similar with respect to their governing forces and magnitude of those forces. Regression models for PP and TP were similar because most P loss resulted from particulate bound P loss. Our results are similar to those by Daverede *et al.* (2004), who determined that sediment loss and STP levels were sufficient for prediction of TP content loss. This commonly occurs as OP values are a source factor and sediment loss is an important transport factor in TP loss.

The DP content loss regression model was less strongly correlated with variables than was DP concentration (Table 5). The best fitting regression model included the variables runoff flow rate (L hr^{-1}, RO) and soil moisture (SM; Table 6). Two levels of soil moisture within the scope of the experiment were used (315 and 400 g kg^{-1}, low and high respectively) to illustrate the relationship between RO and SM with DP content loss (Figure 4). The results imply that greater SM increased DP content loss with increased RO. Soil moisture was not well correlated with runoff ($r = -0.12$), implying that more runoff was not necessarily produced under wetter soil conditions. Greater soil moisture, however, may cause more DP to be present in the soil solution. These results were similar to those found by Torbert *et al.* (1999), who determined that nutrient losses in solution were greater when fertilizer was applied in wet soil conditions.

Regression models for PP and TP content loss both had the same strongly correlated variables and ultimately the same variables were incorporated into the regression model. The terms selected for the model were the two transport variables SED and RO (Table 6). Two levels of sediment loss were selected, 0.20 and 0.80 Mg ha^{-1} (near low and high ranges, respectively, from collected data) to illustrate the relationship of SED and RO with PP and TP content loss (Figure 5, Figure 6). For both PP and TP content loss, P loss increased with increased RO. Increased levels of SED had an additive effect on the model, with

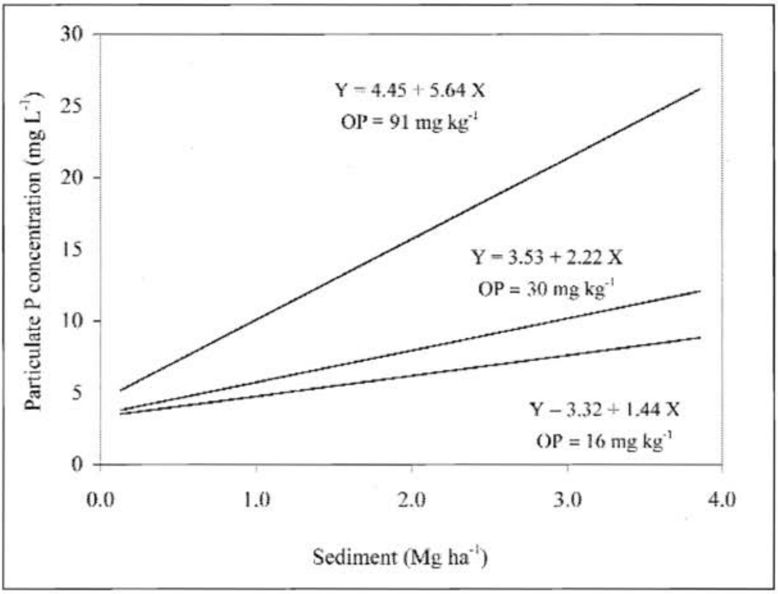

Fig. 2. Response of particulate phosphorus concentration to sediment loss at three levels of Olsen P (OP) soil test (0 - 2.5cm depth).

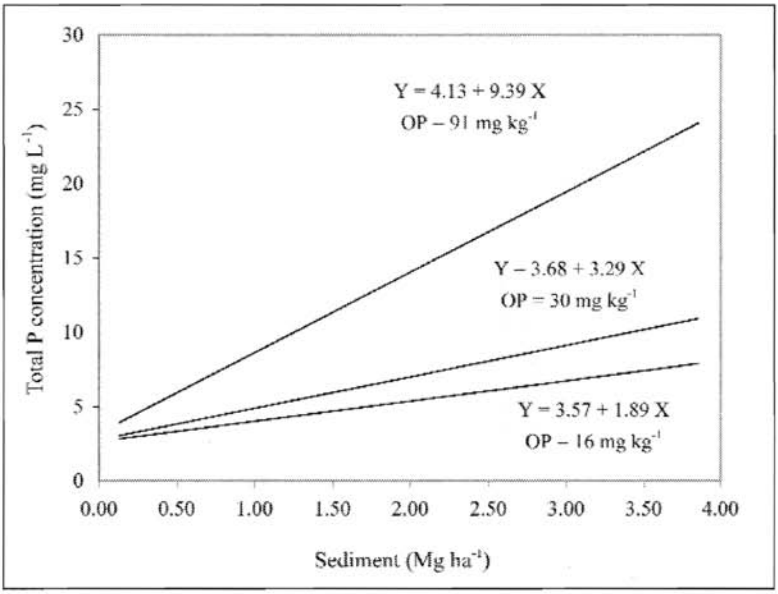

Fig. 3. Response of total phosphorus concentration to sediment loss at three levels of Olsen P (OP) soil test (0 -2.5cm depth).

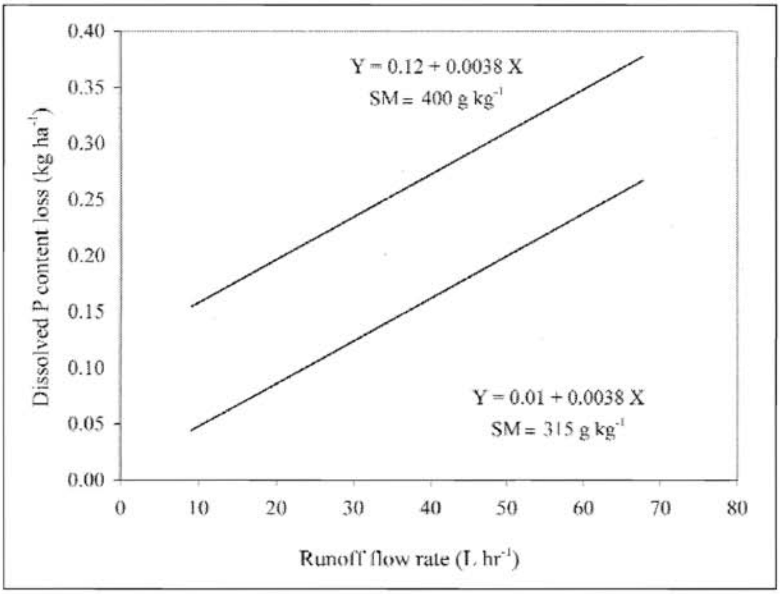

Fig. 4. Response of dissolved phosphorus content loss to runoff flow rate at two levels of soil moisture.

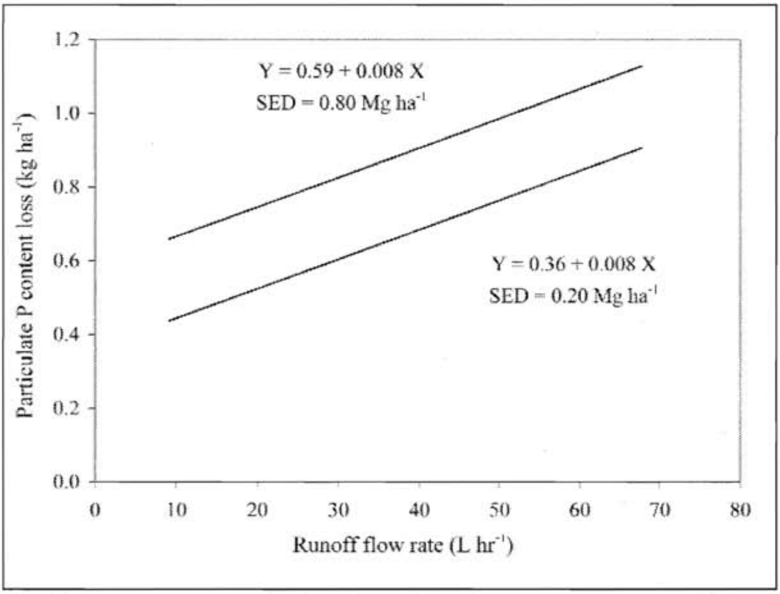

Fig. 5. Response of particulate phosphorus content loss to runoff flow rate at two levels of sediment loss (SED).

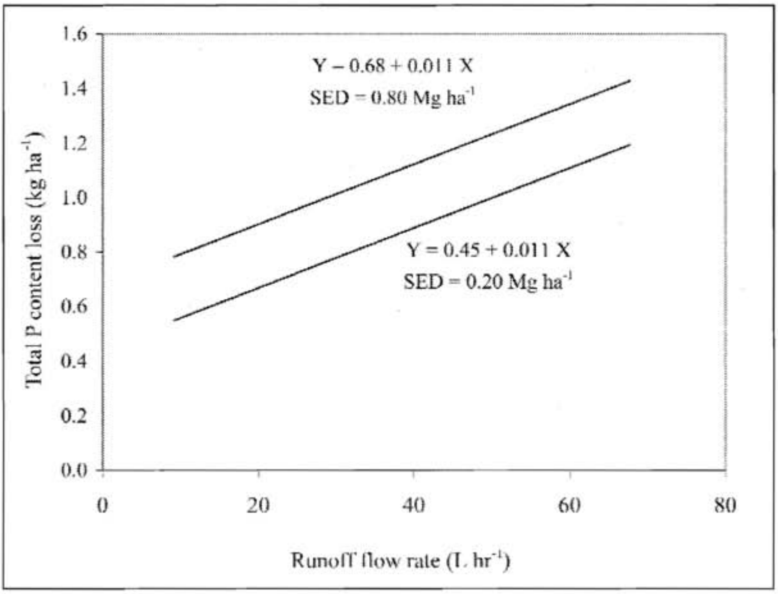

Fig. 6. Response of total phosphorus content loss to runoff flow rate at two levels of sediment loss (SED).

greater P loss from the higher level of SED loss. Also, it is evident that even at SED loss values significantly less that T, runoff flow rate affected PP and TP content losses.

When comparing P content losses on a per hectare basis, transport factors became more influential than source factors. Results demonstrate that the majority of the P lost from the system was in the particulate form. Therefore, erosion driving forces (i.e. transport factors) were the important forces determining TP content loss from sugarbeet fields.

DISCUSSION

Understanding P movement is important when assessing environmental risk to a landscape. Phosphorus can exist in different forms and move in a variety of ways across a landscape. These factors vary in impact depending on how you wish to categorize P loss.

Based on results from this study, it was concluded that P loss was not affected by primary tillage and P fertilization application practices used in sugarbeet production. It was also concluded that P loss from sugarbeet production systems was similar to that in corn/soybean systems. Phosphorus losses were not affected by use of cover crop. Runoff flow rate and sediment loss were also not affected by the management systems evaluated. These results were most likely attributed to the typically low sloping lands used in sugarbeet production and the summer timing of rainfall simulation. The lack of significant slope coupled with secondary tillage/planting effects perhaps nullified any effect of primary tillage or P fertilizer application at the time of rainfall simulation. These results indicate that in order to reduce P losses from sugarbeet production fields, any changes to primary tillage or P fertilizer application detailed in this study may not be effective. More aggressive methods for mitigating P loss will be necessary.

Further analysis was conducted in this study to determine other factors in P loss. It was determined that the Olsen-P soil test was a good indicator of DP concentration in runoff. The Olsen-P soil test, together with sediment loss and their interaction, were good indicators of PP and TP concentration in runoff. For P content losses, runoff flow rate and sediment loss were good indicators. The model for DP content loss included runoff flow rate, soil moisture, and their interaction term.

These regression analysis results indicate that reducing the STP levels will reduce P concentrations in runoff. It is important to note that DP is the most immediately available form of P to algae. Reducing DP concentrations in runoff will likely provide a short-term reduction in environmental problems associated with surface water P (e.g. algal blooms). The majority of STP test values measured in this field study were in the category of very high (i.e. no P fertilizer recommended; Lamb *et al.*, 2001). Therefore, under these conditions, a nutrient management plan to reduce STP values would be both agronomically and environmentally sustainable.

Regression analysis results also indicate that reducing transport factors (runoff and sediment) can effectively reduce P loss, even on low sloping fields. Further reduction of tillage or establishment of a denser cover crop may be possible management options to further reduce P loss from sugarbeet production systems. The effects of these management options need to be more fully explored.

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