SOLUBLE PHOSPHORUS LEACHING FROM CORN SYSTEMS

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ABSTRACT

Equilibrium-tension lysimeters were used to evaluate and compare dissolved reactive phosphorus (DRP) leaching from a prairie and fertilized no-tillage and chisel-plowed corn agroecosystems on Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls) in south central Wisconsin during four monitoring periods, March through April 1996, 1997, and 1998, and from January 1999 through September 2000. A low level of soluble P was found to leach from both natural and managed ecosystems. Dissolved reactive P leaching losses were higher from the managed compared to the natural ecosystems. The fertilized no-tillage agroecosystem consistently maintained higher DRP concentrations in soil leachate solutions compared to the fertilized chisel-plowed agroecosystem, which led to higher DRP leaching losses for the fertilized no-tillage agroecosystem, despite greater drainage from the fertilized chisel-plowed compared to the fertilized no-tillage agroecosystem. Soluble P leaching losses measured for a prairie and fertilized agroecosystems in south central Wisconsin were below acceptable critical limits for P loss.

INTRODUCTION

Phosphorus (P) is a fundamental constituent of the metabolism and biochemistry of all living organisms and, as nitrogen (N) is generally understood as the most limiting nutrient for terrestrial plant growth, the element that commonly limits productivity in freshwater and other aquatic ecosystems (Goltermann and de Oude, 1991; Correll, 1998; Schoumans and Groenendijk, 2000). However, for decades, elevated P levels have led to eutrophication in sensitive surface waters, mainly from diffuse, nonpoint sources of agriculturally-related P (Sims et al., 1998; Hooda et al., 1999). Consequently, much research has been done this subject, but significant and growing problems of P contamination still exist today (Sims et al., 1998).

Historically, most data on P movement in soil have been based on soil analysis of extractable P, which has led to the general assumption that no substantial vertical movement of P occurs because of high P fixation capacity in many mineral soils (Heckrath et al., 1995; Sims et al., 1998; Sui et al., 1999). Soil erosion and surface runoff have typically been focused on as the primary mechanisms of P loss from soil to receiving waters. Although, significant P leaching can occur where certain combinations of land-use practices (i.e., over-fertilization and excessive manuring), soil properties (i.e., sandy subsoil, high organic matter, and the presence of preferential flow paths), and climatic conditions (i.e., precipitation > evapotranspiration) exist (Eghball et al., 1996; Sims et al., 1998). Nonetheless, subsoil leaching of soluble P has generally been considered insignificant and unimportant from agronomic and environmental points of view (Heckrath et al., 1995; Sims et al., 1998; Hesketh and Brookes, 2000). However, recent field studies have indicated the contrary,

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suggesting that soil solution concentrations and subsurface P leaching losses are larger than once thought (Heckrath et al., 1995; Sims et al., 1998; Hooda et al., 1999).

Repeated application of commercial fertilizers, organic wastes, or both to the same fields may saturate the P adsorption capacity of those soils, thus altering the chemical equilibrium established by adsorption/desorption processes (Sims et al., 1998; Schoumans and Groenendijk, 2000). Exceeding the P adsorption capacity will lead to higher concentrations of soluble P in solution and greater potential for P export by subsurface flow paths, which are hydrologically connected to both surface and groundwater.

Much of the recent literature has identified the lack of direct field measurements of soluble P leaching (Mozaffari and Sims, 1994; Heckrath et al., 1995; Sims et al., 1998; Hooda et al., 1999; Hesketh and Brookes, 2000). Seasonal responses to tillage, crop rotations, method and timing of P fertilizer, and manuring must be a research focus in the future if P loss from agricultural soil to sensitive aquatic ecosystems is to be minimized (Sims et al., 1998). One question that needs to be addressed is what is the soluble P concentration and the P load that would leach from various natural and managed ecosystems?

The objective of this study was to use equilibrium-tension lysimeters (ETLs) to evaluate and compare dissolved reactive P (DRP) leaching from a restored prairie and fertilized no-tillage and chisel-plowed corn agroecosystems. Three hypotheses were formulated for this research: 1) a low level of DRP leaches from natural and managed ecosystems, 2) DRP leaching is greater from managed agroecosystems than from natural ecosystems (i.e., restored prairie), and 3) DRP leaching is greater from chisel-plowed than no-tillage agroecosystems.

MATERIALS AND METHODS

Experimental Site and Design

Study sites were established in an agroecosystem and a restored tallgrass prairie in May 1995. The agricultural site is located at the University of Wisconsin's Arlington Agricultural Research Station, Arlington, WI (43° 17' N, 89° 22' E). The prairie is located at the Audubon Society's Goose Pond Sanctuary north of the research station at Arlington, WI. Both sites reside on Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls) at <3% slope and are geographically separated by <2.5 km. At both sites, the soil profile consists of about 2 m of loess over glacial till with a silty-clay-loam subsoil texture. A summary of regional climatic conditions and initial site-specific soil properties is provided in Brye et al. (2000).

A randomized complete-block design was established for corn (*Zea mays* L.) tillage treatments of conventional chisel-plowed and no-tillage in fall 1994 (Brye et al., 2000) (Fig. 1). A 105-day relative maturity hybrid corn variety was planted for each tillage treatment and fertilized at optimum nitrogen (N) rates for corn (Kelling et al., 1991). Fertilized tillage treatments annually received a broadcast application of 190 kg N ha^{-1} as pelletized ammonium nitrate at planting. The agroecosystems also annually received 26 kg P ha^{-1} in the starter fertilizer. For the chisel-plowed treatments, tillage occurred in the fall following harvest and soil conditioning with a disk occurred in the spring before planting.

Four 7- x 7-m plots were established at the prairie site in the spring 1995 (Brye et al., 2000). The prairie was restored from agricultural influence in June 1976; the current vegetation is classified as mesic tallgrass prairie. The prairie was last burned on 18 April 1998.

Precipitation

Hourly precipitation was measured electronically on-site at the prairie using a tipping bucket rain gauge. Similarly, a micrometeorological weather station located <150 m from the agricultural site recorded hourly precipitation with a tipping bucket rain gauge. Additionally, precipitation was collected manually using a funnel collection system for rainfall and a bucket-collection system for snowfall (Brye et al., 2000). Both collection systems were similar to those used by Likens et al. (1977).

Drainage and DRP Leaching

Equilibrium-tension lysimeters (ETLs) were used to monitor drainage and P leaching from the restored prairie and fertilized and unfertilized no-tillage and chisel-plowed corn agroecosystems during a 21-month continuous monitoring period between January 1999 and September 2000 (Brye et al., 1999). Replicate ETLs were installed at 1.4 m below the soil surface in the restored prairie and fertilized tillage treatments during fall 1995 (Fig. 1). Heat dissipation sensors were placed immediately above the porous plate of each ETL and in the surrounding bulk soil to continuously monitor the matric potential at the two locations (Reece, 1996; Brye et al., 1999). A portable, regulated vacuum system provided continuous suction to the 0.2-µm stainless steel porous plate of the ETLs (Brye et al., 1999). The regulated vacuum system was adjusted manually several times a week to provide suction that was slightly more negative (i.e., a few kilopascals) than the matric potential recorded in the surrounding bulk soil with the heat dissipation sensors.

The lysimeters were sampled under vacuum every 2 weeks between March and December and once every 4 weeks during the rest of the year (Brye et al., 1999). Leachate was collected from the lysimeter's collection reservoir, which contains ~ 23 L or ~ 110 mm of water, through a sampling tube that extends from a drain port on the lysimeter to the soil surface. The initial leachate up to 1 L was collected into a 1-L high-density polyethylene bottle and transported back to the laboratory where the leachate volume was measured. Any remaining leachate from the lysimeters, >1 L, was collected, volumes were recorded, and the leachate was discarded. Subsample aliquots of the initial 1 L of leachate were filtered through glass fiber filter paper (Whatman G6) and stored at 4^{o} C until chemical analysis could be performed.

Lysimeter leachate samples from the 21-month monitoring period were analyzed for dissolved reactive phosphorus (DRP) using the ascorbic acid color development method (Murphy and Riley, 1962) and analyzed on a Beckman DU 640 spectrophotometer

(Beckman Coulter, Inc., Fullerton, CA). Additionally, stored lysimeter leachate samples from the months of March and April 1996, 1997, and 1998 were analyzed for DRP.

Statistical Analyses

A one-way analysis of variance (ANOVA) was performed for cumulative drainage and DRP concentrations and leaching losses for each measurement period (Minitab, 1997).

RESULTS AND DISCUSSION

Precipitation and Drainage

Precipitation inputs throughout the 21-month continuous drainage and DRP-leaching monitoring period (i.e., between January 1999 and September 2000) were generally higher than 30-yr averages for the Arlington Agricultural Research Station during the months of January through July for both years and generally lower than 30-yr averages during remaining months (Owenby and Ezell, 1992) (Fig. 2). Cumulative measured precipitation during this 21-month period was 220 mm greater than cumulative precipitation based on 30-yr averages.

The prairie ecosystem received roughly 100 mm less precipitation than the agroecosystems during the 21-month monitoring period between January 1999 and September 2000 (Table 1). During this time, drainage was largest from the fertilized chisel-plowed agroecosystem and smallest from the prairie. However, cumulative drainage differences among ecosystems were not significantly different due to large drainage variations between sample replicates for numerous sample dates during the 21-month continuous monitoring period. The prairie and agroecosystems received the same amount of precipitation during March through April 1996, 1997, and 1998 (Table 1). Similarly, mean drainage was always higher from the fertilized chisel-plowed agroecosystem, but drainage did not differ significantly among ecosystems for the March through April period in 1996 or 1998. However, drainage from the fertilized chisel-plowed agroecosystem between March and April 1997 was significantly greater (p-value = 0.001) than drainage from the prairie or fertilized no-tillage agroecosystem.

DRP Concentrations

Mean DRP concentrations in ETL leachate solutions from 1.4 m below the soil surface were highest in the fertilized no-tillage agroecosystem (NTf) than the prairie (GP) or fertilized chisel-plowed agroecosystem (CPf) for nine of 12 sample dates during March and April 1996, 1997, and 1998 (Fig. 3). Overall, mean DRP concentrations during March through April 1996, 1997, and 1998 were highest for the fertilized no-tillage agroecosystem compared to the other two ecosystems (Fig. 3). Mean DRP concentrations were significantly higher, at the 5% level, for the fertilized agroecosystems (p-value = 0.050) compared to the prairie for only the 21 April 1996 sample date.

Mean DRP concentrations were consistently higher for the fertilized no-tillage agroecosystem compared to the prairie and fertilized chisel-plowed agroecosystem during

Table 1. Summary of precipitation and equilibrium-tension-lysimeter-recorded drainage for four different time periods between March 1996 and September 2000 for the restored Goose Pond prairie and fertilized no-tillage and chisel-plowed corn agroecosystems. Standard errors for cumulative drainage measurements are reported in parentheses. Analysis of variance (ANOVA) results are reported to denote statistically significant differences in drainage among ecosystems for the various time periods of measurements.

Period/Measurement	**Ecosystems**			**ANOVA p-value**
	Prairie	**Fertilized No-Tillage**	**Fertilized Chisel-Plowed**	
March - April 1996				
Precipitation (mm)	70.4	68.0		
Drainage (mm)	12.9 (5.5)	31.6 (12)	44.7 (6.6)	0.168
March - April 1997				
Precipitation (mm)	60.2	60.4		
Drainage (mm)	25.9 (3.6)	46.3 (4.2)	108 (2.7)	0.001
March - April 1998				
Precipitation (mm)	212	212		
Drainage (mm)	74.3 (0.1)	142 (25)	226 (47)	0.086
January 1999 - September 2000				
Precipitation (mm)	1547	1650		
Drainage (mm)	211 (7.3)	531 (19)	820 (226)	0.101

the 21-month, January 1999 through September 2000, monitoring period (Fig. 4). Mean DRP concentrations for the 21-month period were 0.07, 0.04 and 0.02 mg DRP L^{-1} for the fertilized no-tillage, fertilized chisel-plowed, and prairie ecosystems, respectively. Mean DRP concentrations for the March through April periods of 1999 and 2000 were 0.06, 0.02, and 0.01 mg DRP L^{-1} and 0.09, 0.06, and 0.01 mg DRP L^{-1} for the fertilized no-tillage, fertilized chisel-plowed, and prairie ecosystems, respectively. Several large DRP concentration spikes (i.e., >0.15 mg DRP L^{-1}) were recorded during spring 1999, but repeated chemical analysis suggested the spikes were not due to leachate sample contamination. Mean DRP concentrations differed significantly (p-values <0.01) among ecosystems for 10 of the 32 sample dates during the 21-month monitoring period (Fig. 4).

Though the movement of soluble P has really only gained attention in recent years, several studies have reported soluble P concentrations in soil leachate solutions collected from a variety of sources, such as zero-tension lysimeters and tile drains. The soluble P concentrations reported in this study fall within the range reported for agricultural soil leachate solutions, which vary from below detection limits to as high as 1.5 mg L^{-1} for molybdate-reactive P (Sims et al., 1998).

For many of the drainage and DRP measurement dates during spring 1996, 1997, and 1998 and during the 21-month continuous monitoring period, mean DRP concentrations for the fertilized agroecosystems were within or above the threshold range of total P concentrations (i.e., 0.01 to 0.05 mg P L^{-1}) associated with eutrophication of surface waters (Sims et al., 1998). Even though the DRP concentrations reported in ths study are for soil leachate solutions at 1.4 m below the soil surface, subsurface lateral flow and groundwater flow patterns make soil leachate solutions potentially hydrologically connected with surface waters. Additionally, Correll (1998) recognized that soluble P concentrations of 1 mg L^{-1} are unacceptably high in surface waters and that concentrations of 0.02 mg L^{-1} are frequently problematic.

DRP Leaching

Despite consistently higher DRP concentrations under the fertilized no-tillage compared to the fertilized chisel-plowed agroecosystem during March and April 1996, 1997, and 1998 (Fig. 3), DRP leaching losses during these times were generally larger for the fertilized chisel-plowed compared to the fertilized no-tillage agroecosystem due to the differences in drainage between the two tillage treatments (Table 1). Prairie DRP leaching losses were always smaller than for the agroecosystems. Mean DRP leaching losses per sampling period (i.e., ~2 weeks) were 0.29, 0.84, and 1.27 g DRP ha^{-1} in 1996, 0.02, 1.31, and 2.31 g DRP ha^{-1} in 1997, and 1.06, 16.5, and 10.0 g DRP ha^{-1} in 1998 for the prairie, fertilized no-tillage, and fertilized chisel-plowed ecosystems, respectively. Significant differences, at the 5% level, among ecosystems for DRP leaching losses were observed for only the 19 April 1998 sampling date. Cumulative DRP leaching losses for the 2-month period were 1.2, 2.8, and 3.9 g DRP ha^{-1} in 1996, 0.09, 6.6, and 12 g DRP ha^{-1} in 1997, and 3.1, 52, and 30 g DRP ha^{-1} in 1998 for the prairie, fertilized no-tillage, and fertilized chisel-plowed ecosystems, respectively (Fig. 3).

In contrast to DRP concentration pattens for the four monitoring periods (i.e., March through April 1996, 1997, 1998, and January 1999 through September 2000) and leaching loss patterns observed during March through April 1996, 1997, and 1998, mean DRP leaching losses were higher, on a per sample date basis, for the fertilized no-tillage agroecosystems compared to the fertilized chisel-plowed agroecosystem and prairie (Fig. 5). Dissolved reactive phosphorus leaching losses differed significantly, at the 5% level, among ecosystems on 20 March 1999 and 22 April 2000. Cumulative DRP leaching losses for the 21-month continuous monitoring period were 37.6, 237, and 328 g DRP ha^{-1} for the prairie, fertilized chisel-plowed, and fertilized no-tillage ecosystems, respectively (Fig. 5). Cumulative DRP leaching losses from the fertilized agroecosystems were significantly higher (p-value = 0.08) than DRP losses from the prairie.

Similarly to the DRP concentrations found in this study, DRP leaching losses also fall into the range of P losses reported for agricultural soil leachate solutions (Sims et al., 1998). Duxbury and Peverly (1978) reported molybdate-reactive P (MRP) losses of 0.03 to 31 kg ha^{-1} yr^{-1} for uncultivated and cultivated tile-drained soils. However, soluble P losses of <1 kg P ha^{-1} yr^{-1} are more common (Sims et al., 1998). Nonetheless, soluble P leaching losses measured for a prairie and fertilized agroecosystems in south central Wisconsin were still below acceptable critical limits for P loss, which are ~400 g P ha^{-1} yr^{-1} (Stamm et al., 1997).

SUMMARY AND CONCLUSIONS

Equilibrium-tension lysimeters were used to evaluate and compare DRP leaching from a prairie and fertilized no-tillage and chisel-plowed corn agroecosystems on silt loam soil in south central Wisconsin during four monitoring periods, March through April 1996, 1997, and 1998, and from January 1999 through September 2000. A low level of soluble P, generally <0.05 mg P L^{-1}, was found to leach from both natural and managed ecosystems. Dissolved reactive phosphorus leaching losses were higher from the managed, fertilized agroecosystems compared to the natural, restored prairie. However, despite higher drainage from the fertilized chisel-plowed agroecosystem, the no-tillage agroecosystem consistently maintained higher DRP concentrations in soil leachate solutions at 1.4 m below the soil surface, which led to higher DRP leaching losses for the fertilized no-tillage compared to the fertilized chisel-plowed agroecosystem. Nonetheless, soluble P leaching losses measured for a prairie and fertilized agroecosystems in south central Wisconsin were still below acceptable critical limits for P loss.

REFERENCES

Bray, R.H, and L.T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soil. Soil Sci. 59:39-45.

Brye, K.R., J.M. Norman, L.G. Bundy, and S.T. Gower. 1999. An equilibrium tension lysimeter for measuring drainage through soil. Soil Sci. Soc. Am. J. 63:536-542.

Brye, K.R., J.M. Norman, L.G. Bundy, and S.T. Gower. 2000. Water budget evaluation of prairie and maize ecosystems. Soil Sci. Soc. Am. J. 64:715-724.

Correll, D.L. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. J. Environ. Qual. 27:261-266.

Duxbury, J.M., and J.H. Peverly. 1978. Nitrogen and phosphorus losses from organic soils. J. Environ. Qual. 7:566-570.

Eghball, B., G.D. Binford, and D.D. Baltensperger. 1996. Phosphorus movement and adsorption in a soil receiving long-term manure and fertilizer applications. J. Environ. Qual. 25:1339-1343.

Goltermann, H.L., and N.T. de Oude. 1991. Eutrophication of lakes, rivers and costal seas. p.

79-124. *In* O. Hutzinger (ed.) The handbook of environmental chemistry. Vol. 5. Part A. Water pollution. Springer Verlag, Berlin, Germany.

Heckrath, G., P.C. Brookes, P.R. Poulton, and K.W. T. Goulding. 1995. Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk Experiment. J. Environ. Qual. 24:904-910.

Hesketh, N., and P.C. Brookes. 2000. Development of an indicator for risk of phosphorus leaching. J. Environ. Qual. 29:105-110.

Hooda, P.S., M. Moynagh, I.F. Svoboda, A.C. Edwards, H.A. Anderson, and G. Syn. 1999. Phosphorus loss in drainflow from intensively managed grassland soils. J Environ. Qual. 28:1235-1242.

Kelling, K.A., L.G. Bundy, S.M. Combs, and J.B. Peters. 1991. Soil test recommendations for field, vegetable, and fruit crops. Univ. of Wisconsin-Extension. A2809.

Likens, G.E., F.H. Bormann, R.S. Pierce, J.S. Eaton, and N.M. Johnson. 1977. Biogeochemistry of a forested ecosystem. Springer-Verlag, New York.

Minitab Inc. 1997. Minitab user's guide 12th ed. Volumes 1-2. Minitab Inc, State College, Pa.

Mozaffari, M., and J.T. Sims. 1994. Phosphorus availability and sorption in an Atlantic coastal plain watershed dominated by animal-based agriculture. Soil Sci. 157:97-107.

Murphy, J., and J.R. Riley. 1962. A modified single solution method for the determinations of phosphate in natural waters. Anal. Chem. 27:31-36.

Owenby, J.R., and D.S. Ezell. 1992. Monthly station normals of temperature, precipitation, and heating and cooling degree days 1961-90. U.S.Department of Commerce, National Climatic Data Ctr, Ashville, NC.

Reece, C.F. 1996. Evaluation of a line heat dissipation sensor for measuring soil matric potential. Soil Sci. Soc. Am. J. 60:1022-1028.

Schoumans, O.F., and P. Groenendijk. 2000. Modeling soil phosphorus levels and phosphorus leaching from agricultural land in the Netherlands. J. Environ. Qual. 29:111-116.

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.

Sui, Y., M.L. Thompson, and C.W. Mize. 1999. Redistribution of biosolids-derived total phosphorus applied to a mollisol. J. Environ. Qual. 28:1068-1074.

Stamm, C., R. Gachter, H. Fluhler, J. Leuenberger, and H. Wunderli. 1997. Phosphorus input to a brook through tile-drains under grassland. p. 372-373. *In* H. Tunney et al. (ed.) Phosphorus losses from soil to water. CAB Int., Wallingford, UK.