Soil controls of phosphorus in runoff: Management barriers and opportunities

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[1]USDA-ARS, Pasture Systems and Watershed Management Research Unit, University Park, PA 16802, USA (e-mail: peter.kleinman@ars.usda.gov); [2]Department of Crop, Soil and Environmental Sciences, University of Arkansas, Fayetteville, AR 72701, USA; [3]AgResearch Ltd, Invermay Agricultural Centre, Mosgiel, New Zealand; and [4]Department of Agriculture, Food & Resource Sciences, University of Maryland Eastern Shore, Princess Anne, MD 21853, USA. Received 18 November 2009, accepted 12 July 2010.

Kleinman, P. J. A., Sharpley, A. N., Buda, A. R., McDowell, R. W. and Allen, A. L. 2011. **Soil controls of phosphorus in runoff: Management barriers and opportunities**. Can. J. Soil Sci. **91**: 329–338. The persistent problem of eutrophication, the biological enrichment of surface waters, has produced a vast literature on soil phosphorus (P) effects on runoff water quality. This paper considers the mechanisms controlling soil P transfers from agricultural soils to runoff waters, and the management of these transfers. Historical emphases on soil conservation and control of sediment delivery to surface waters have demonstrated that comprehensive strategies to mitigate sediment-bound P transfer can produce long-term water quality improvements at a watershed scale. Less responsive are dissolved P releases from soils that have historically received P applications in excess of crop requirements. While halting further P applications to such soils may prevent dissolved P losses from growing, the desorption of P from soils that is derived from historical inputs, termed here as ‘‘legacy P’’, can persist for long periods of time. Articulating the role of legacy P in delaying the response of watersheds to remedial programs requires more work, delivering the difficult message that yesterday’s sinks of P may be today’s sources. Even legacy sources of P that occur in low concentration relative to agronomic requirement can support significant loads of P in runoff under the right hydrologic conditions. Strategies that take advantage of the capacity of soils to buffer dissolved P losses, such as periodic tillage to diminish severe vertical stratification of P in no-till soils, offer short-term solutions to mitigating P losses. In some cases, more aggressive strategies are required to mitigate both short-term and legacy P losses.

Key words: Phosphorus, runoff, eutrophication, nutrient management, no till

Kleinman, P. J. A., Sharpley, A. N., Buda, A. R., McDowell, R. W. et Allen, A. L. 2011. **Régulation des pertes de P dans l’eau de ruissellement par le sol: obstacles et possibilités en matière de gestion**. Can. J. Soil Sci. **91**: 329–338. Le problème persistant de l’eutrophisation (l’enrichissement biologique des eaux superficielles) a engendré une foison de documents traitant des effets du phosphore (P) du sol sur la qualité des eaux de ruissellement. Cet article examine les mécanismes qui commandent le transfert du P des sols arables aux eaux de ruissellement, et la manière dont on pourrait gérer de tels transferts. La longue insistance sur l’utilité de préserver le sol et de maîtriser le déversement des sédiments dans les eaux de surface prouve qu’à longue échéance, les stratégies intégrées visant à atténuer le transfert du P associé aux sédiments améliorent la qualité de l’eau des bassins hydrographiques. Le P libéré par dissolution des sols auxquels on a historiquement appliqué une quantité excessive de cet élément, comparativement à ce que réclamaient les cultures, répond toutefois moins bien à de telles stratégies. Si interrompre l’application de P à de tels sols pourrait interdire une hausse supplémentaire des pertes de P dissous, la concentration de P résultant des amendements passés (le P historique) pourrait mettre beaucoup plus de temps à se résorber. Établir dans quelle mesure le P historique peut retarder la réaction des bassins hydrographiques aux programmes de restauration nécessitera des travaux plus poussés, signe malheureux que les sols qui servaient naguère de puits au P en sont devenus des sources aujourd’hui. Même les sources historiques de P peu importantes en regard des besoins des plantes peuvent libérer une quantité sensible de P dans l’eau de ruissellement si les bonnes conditions hydrologiques s’y prêtent. Les stratégies qui tirent parti de la capacité des sols à compenser les pertes de P dissous, comme le travail périodique de la terre en vue d’atténuer une trop grande stratification verticale du P dans les sols non labourés, constituent des solutions à court terme pour atténuer les pertes de P. Dans certains cas cependant, il conviendrait d’adopter des stratégies plus énergiques si l’on veut réduire tant les pertes de P à court terme que les pertes de P historique.

Mots clés: Phosphore, ruissellement, eutrophisation, gestion des éléments nutritifs, non-travail du sol

The transport of phosphorus (P) from agricultural soils to surface waters remains a priority concern in many areas of the world, with P the primary control of eutrophication in many freshwater bodies (Carpenter et al. 1998). Even in regions with long-established mitigation programs, such as the Great Lakes of North America, accelerated eutrophication remains difficult to control. Diffuse, or non-point source, pollution now dominates

P loadings to many water bodies, replacing point source pollution as the primary target of today's remedial strategies. Over the past 15 yr, an enormous body of research has examined the processes contributing to non-point source P loads, from which a new generation of P management practices and strategies has ensued.

One of the major differences between past and present approaches to non-point source P pollution management is the current emphasis on controlling both sediment-bound and dissolved forms of P in runoff, as opposed to sediment-bound forms only. Outside of a few landscapes, dissolved P runoff was largely ignored until the 1990s. With the establishment of specialized, intensive production systems has come the recognition that dissolved P in runoff can become a primary water quality concern to agriculture (Sharpley et al. 1994). To aid agricultural P management, site assessment indices have been widely promoted, identifying locations where soil and applied P sources combine with high transport potential to aggravate P loss in runoff (Sharpley et al. 2003).

Site assessment indices distinguish between two categories of sources responsible for non-point source P pollution from agriculture (Lemunyon and Gilbert 1993): (1) soils and (2) applied P fertilizers and manures. To some extent, this split misses the interaction between soil and the applied sources. Even so, the separation of these two source categories shows soil P to be a long-term, or chronic, source that continuously impacts runoff water quality while fertilizer and manure P are sources whose transfer to runoff water (also termed ‘‘incidental transfer’’ by Preedy et al. (2001) tend to be large, but short-lived. It follows that the management of soil P transfer to runoff needs to consider both short- and long-term solutions.

Soil has traditionally been considered a sink for P, but it is well established that the capacity of a soil to convert P from labile to stable phase declines as P accumulates (Kleinman et al. 2000). All soils will lose dissolved and sediment-bound P to runoff, but the potential for dissolved P loss to runoff from P-enriched soils is greater than from P-limited soils (Vadas et al. 2005). Because it can take a long time for soil P concentrations to decline (McCollum 1991; Schärer et al. 2007), dissolved P desorption from soils persists for long periods of time (Sharpley and Rekolainen 1997). Dissolved P that is desorbed from soils and sediments to waters may be considered ‘‘legacy P’’, as it derives from past applications of P to soil. Today, the role of legacy P in delaying the response of watersheds to remedial programs is not well understood.

Another obstacle to water quality improvement is the uncertainty associated with predicting the role of hydrologic processes in non-point source P pollution. The timing, location and magnitude of hydrologic flow pathways have been largely overlooked in agricultural settings, particularly at the fine spatial and temporal scales that are meaningful to management. For example, in watersheds with grazed pastures, impermeable areas associated with stock camping or animal tracks can account for most of the P lost in small storms (McDowell and Srinivasan 2009). Furthermore, hydrologic processes operating on a landscape scale can readily overwhelm management practices intended to curtail runoff and soil P transfers (Haygarth et al. 2000; Heathwaite and Dils 2000). Moreover, as P concentrations in agricultural soils have increased with time, pathways deemed relatively unimportant to P export in the past are now being recognized as more significant (e.g., Sims et al. 1998).

This paper seeks to illuminate critical controls of soil P transfers from agricultural lands, highlighting obstacles to water quality mitigation efforts and opportunities for action.

SOURCES AND MANAGEMENT OF SEDIMENT-BOUND P TRANSPORT

Although the recent literature on runoff P losses has been dominated by work on dissolved P transfers, soil erosion and associated particulate P transport remain the priority water quality concern for P (Sims and Kleinman 2005). Unchecked, erosion can overwhelm other sources of P loss, and therefore remains the first target of remedial action strategies in sloping landscapes. Erosion preferentially removes fine soil particles that are enriched with P relative to bulk soil, resulting in enrichment ratios (P concentration of sediment: P concentration of bulk soil) that are generally at least 2:1 and up to 15:1 (Fig. 1). Although sediment P enrichment ratios tend to decline with increasing rates of erosion (and greater removal of larger soil particles and aggregates), there is a strong negative correlation between soil surface cover and enrichment ratio (Sharpley et al. 2002). Therefore, the more effective the erosion controls of a particular cropping system, the lower the relative enrichment of sediment-bound P in runoff.

The beneficial effects of soil conservation on field-scale P losses are generally well established. However, the processes controlling sediment-P losses at a field scale may shift significantly over time. Sharpley and Smith (1994) summarized long-term (1977–1990) runoff observations from fields (1.6–2.9 ha) in Oklahoma, USA, where mineral fertilizer was applied. Native grassland watersheds were converted to tilled wheat (plowed and disked) in 1979. In the ensuing years, erosion increased an average of 57-fold (roughly 10-fold for most fields) and total P losses increased 10-fold compared with native grasslands, with sediment-bound P accounting for 58–96% of total P in runoff. Contributing to the increase in total P losses were: (a) greater sediment-bound P concentrations in runoff from tilled soils, a function of detatchment and erosion of exposed, destabilized soils; and (b) greater runoff volumes from tilled soils, a function of lowered rainfall infiltration capacity induced by removal of surface cover, slaking of aggregates on the soil surface, crusting then sealing.

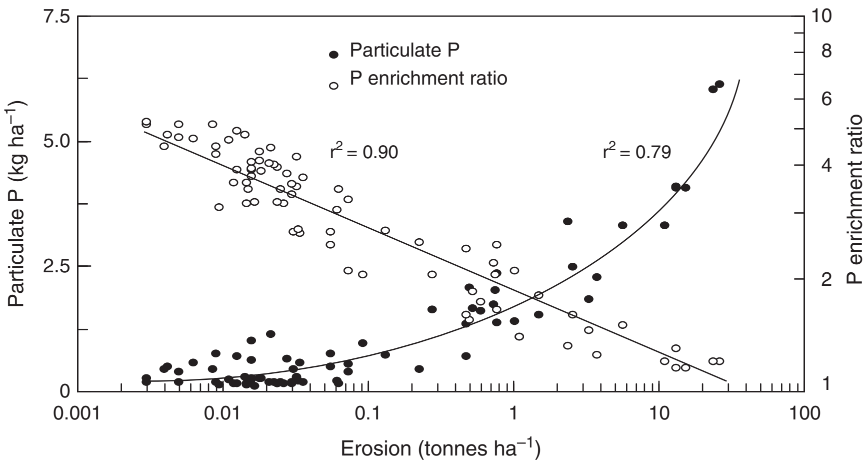


Fig. 1. Particulate P loss and P enrichment ratio of eroded sediment relative to bulk soil as a function of erosion in overland flow from watersheds in Oklahoma, USA. Adapted from Sharpley et al. (1991) and Smith et al. (1991).

When a subset of the tilled fields was eventually converted to no-till (from 1982 to 1984), the yield of sediment-bound P declined, but only by a factor of two, a fraction of the increase in sediment-P loss induced by converting native grassland to cropland. This time, the change in sediment-bound P losses reflected lower sediment concentrations in runoff with no-till than with tillage, but there were no significant changes in runoff volumes, even 7 yr following conversion to no-till.

As scale increases from field to watershed, so too does the array of processes affecting sediment-bound P transfers and the required complexity of strategies to stop sediment-bound P losses. Sediment-bound P exported from watersheds derives from a series of erosion and deposition events. In general, sediment delivery ratios decline with watershed size as physiography and management become more heterogeneous (Novotny and Olem 1994). Moreover, certain sediment sources representing small areas within a watershed, such as stream bank soils and relic mill pond sediments, may disproportionately contribute to watershed sediment export (Zaimes et al. 2004; Walter and Merrits 2008). For example, in a dairy-farmed watershed in New Zealand, McDowell and Wilcock (2007) traced the majority of annual sediment-associated P load to stream bank erosion during winter and spring, but field runoff accounted for a greater proportion of sediment-bound P load during the biologically active periods of summer and fall. Thus, in order to be effective at controlling sediment-bound P losses at a watershed scale, soil conservation strategies must address an array of sources and be effective year-round (Sharpley et al. 2009).

Comprehensive strategies to mitigate watershed export of sediment-bound P must include both soil conservation and sediment interception measures. Monitoring of Lake Erie's Agricultural Systems for Environmental Quality (LEASEQ) watersheds, the Maumee River Watershed (17 115 km^2) and the Sandusky River Watershed (3240 km^2) demonstrates the extent to which sediment-bound P reductions can be achieved (Richards et al. 2002). The LEASEQ watersheds are primarily in agriculture (>85%), most of which consists of row crop production. From 1987 to 1997, an average of $7000 per farm was spent in the Maumee and Sandusky River watersheds to decrease P and sediment loadings. Two-thirds of these expenditures were associated with USDA's Conservation Reserve Program, which facilitated implementation of practices such as no till, cover crops, buffers, grass waterways, diversion drainage, and sediment retention structures. By 1995, soil conservation and sediment control practices had been implemented on 85 and 97% of the erodible land in the Maumee River and Sandusky River watersheds, respectively (Baker and Richards 2002). Lesser emphasis was placed on practices that would be expected to impact dissolved P export, and soil test P actually increased in agricultural soils during the study period (Baker and Richards 2002; Forster and Rausch 2002). However, from 1975 to 1995, total P export from the two watersheds, of which 85% was sediment-bound P, declined by 25 and 40% (Baker and Richards 2002). Since then, sediment-bound P exports have remained low (Richards 2009).

SOURCES AND MANAGEMENT OF DISSOLVED P IN RUNOFF

The transfer of dissolved P from agricultural soils to runoff water is profoundly buffered by both P adsorption and precipitation processes. While additions of fertilizers and manures to soil temporarily overwhelm the balance between P in solution and solid phase, with time these equilibrate with the soil in readily available forms that, without further P additions, transform into more recalcitrant P forms. Buffering of dissolved P additions has been a great benefit to water quality in the past, as it minimizes the effect of surplus applications of

P to soils, but, left unchecked, surplus P applications eventually convert soils from sinks to sources of dissolved P.

The conceptual pools of Quantity (Q, or P sorbed to soil solids) and Intensity (I, or P in solution), long employed in the study of soil fertility, are also useful in describing the contrasting role of soils as sinks and sources of dissolved P in runoff (Koopmans et al. 2002). Maguire et al. (2002) described a non-linear interaction between soils of differing P buffer capacities ($Q\ I^{-1}$). They found that soils with greater P buffer capacities exert a greater influence on P in solution than do soils that have lesser P buffer capacities. As illustrated in Fig. 2, when two soils with varying P buffer capacities were mixed in varying proportions, their combined effect on P in solution was primarily determined by the soil with the stronger buffer capacity. The implication of this non-linear interaction is that well-buffered soils (and their sediments) that intercept runoff pathways temporarily mask upslope and upstream contributions of dissolved P. In the past, strong buffers to dissolved P were ubiquitous along flow pathways, sorbing much of the dissolved P that was released from soils to runoff, even during runoff (Sharpley et al. 1981). However, with continual input of fertilizer and manure P sources, traditionally reliable soil buffers of dissolved P can eventually be overwhelmed as a result of P sorption saturation.

The concept of ''soil P sorption saturation'' (also ''soil P saturation'' and ''degree of P saturation'') achieved prominence in the 1990s as metric of a soil's tendency to support dissolved P concentrations in water (Sharpley and Rekolainen 1997):

$$\text{Soil P sorption saturation} = \text{sorbed P/P sorption saturation} \quad (1)$$

Soil P sorption saturation has been used to quantify dissolved P concentrations in both surface runoff (Pote et al. 1996; Hughes et al. 2006) and leaching waters (Breeuwsma and Silva 1992; Maguire and Sims 2002). Thresholds of P sorption saturation were proposed by a variety of authors to identify the point of P accumulation by a soil at which environmental losses of dissolved P would significantly increase (Sibbesen and Sharpley 1997; Schoumans and Groenendijk 2000). To this day, P sorption saturation remains a regularly cited environmental indicator, albeit with more limited use than a decade ago. A substantial number of studies demonstrate that various soil P extraction methods, including common agronomic tests, relate well to soil P sorption saturation (Kleinman et al. 1999; Pautler and Sims 2000). Furthermore, it has been shown that these tests relate equally well to concentrations of dissolved P in runoff and leaching water (Pote et al. 1999; McDowell and Sharpley 2001; Torbert et al. 2002). In an analysis of literature data, McDowell and Condron (2004) and Vadas et al. (2005) concluded that common agronomic soil tests were as good as P sorption saturation in quantifying dissolved P concentration in runoff from a wide range of soils (Fig. 3). They argued that prediction of dissolved P release from soils to runoff could be effectively achieved via a limited set of relationships such as the quotient of soil test P and the P sorption index of Bache and Williams (1971). The P sorption index relates sorbed P with the log of solution P derived from a single point P sorption isotherm and is highly correlated with P sorption maximum (Bache and Williams 1971).

The ability to predict dissolved P concentrations in runoff has been key to the adoption of P site assessment indices in the United States of America and to their use in recommending whether additional P should be applied to a soil (Sharpley et al. 2003). However, behind their development a central question has been: at what level of soil P do dissolved P losses in runoff require remedial response? As no regulatory guidance exists for P concentrations in runoff waters, initial proposals were to apply recommended P concentrations in effluent from

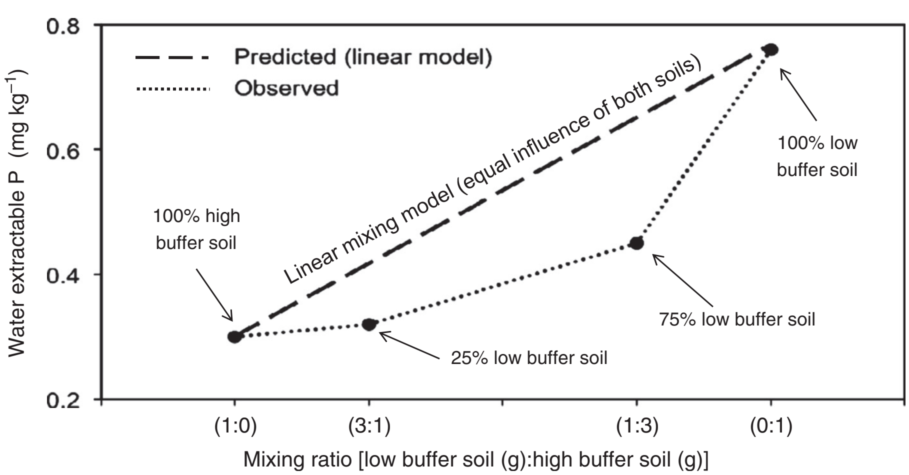


Fig. 2. Effect of mixing two soils with low (soil 1) and high (soil 2) P buffer capacities. Adapted from Maguire et al. (2002).

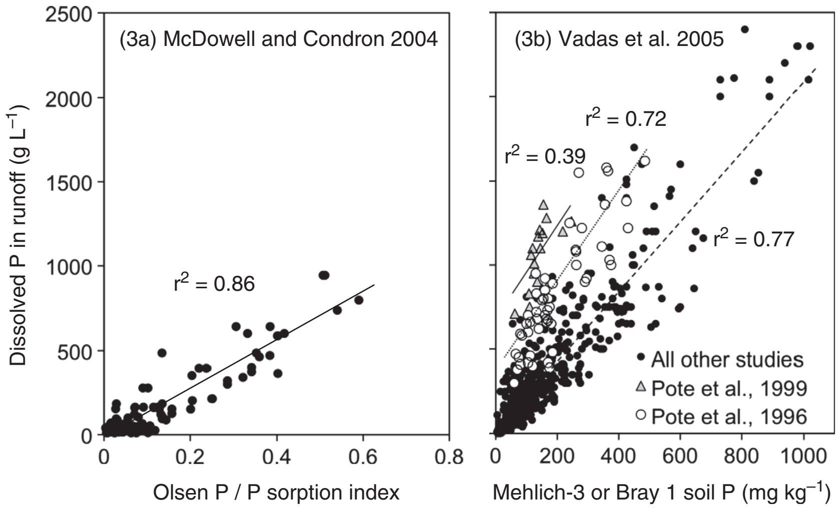


Fig. 3. Relationship of dissolved P concentration in runoff with (a) the quotient of Olsen soil P and the soil P sorption index [adapted from McDowell and Condron (2004)], and (b) Mehlich-3 and Bray 1 soil P concentration [adapted from Vadas et al. (2005)].

wastewater facilities (e.g., 1 mg L^{-1}) to soil P/runoff P relationships, using the corresponding soil P value as an environmental threshold (Daniel et al. 1994).

Studies evaluating soil P sorption saturation and other non-agronomic tests (e.g., water or dilute salt extracts) suggested the presence of statistically identifiable thresholds for P release that could be used to define soil P thresholds above which P additions should not be added due to greater potential for dissolved P loss to water (Kleinman et al. 2000; McDowell and Sharpley 2001; Butler and Coale 2005). These statistical thresholds, however, have generally not been observed in field studies, even those involving highly controlled rainfall simulations on small plots (Vadas et al. 2005), and do not translate well to downslope or downstream P concentrations.

There have been continuous calls to employ crop response thresholds to guide both agronomic and environmental P management decisions, but strong arguments have existed that agronomic and environmental P thresholds are not necessarily the same (Daniel et al. 1994). Therefore, no science-based consensus exists to this day on how to identify and employ soil P thresholds to address the problem of dissolved P transfers from soils. While soil P thresholds could be set at levels above which there is no plant response to added P, these levels do not necessarily relate to an increased potential for P loss in runoff due to the many other confounding site factors that determine P loss already discussed (Sharpley et al. 2007). Thus, it remains unrealistic to envisage environmental thresholds that are directed at reducing the risk of dissolved or particulate P loss to surface waters to be based solely on soil P levels without considering site hydrology and management.

Nowhere is the dilemma of P sorption saturation and dissolved P release from soil more apparent than with reduced tillage management. Today, nearly 40% of US cropland is in some form of reduced tillage, which continues to expand across North America (Conservation Tillage Information Center 2009). It is well established that P accumulates in the surface of soils as a result of repeated applications of fertilizers and manures (Hooda et al. 2001), and that vertical stratification of P in soils is most severe in soils that are not tilled (Selles et al. 1997; Holanda et al. 1998). It is also well established that runoff water interacts with the top 0.1–4 cm of soil, termed the effective depth of interaction (Sharpley 1985). Tillage, therefore, represents an effective means of moving P from the effective depth of interaction and, depending upon tillage type, mixing enriched topsoil P with deeper soil, thereby reducing P losses in runoff (Gaynor and Findlay 1995; Daverede et al. 2003; Sharpley 2003; Quincke et al. 2007).

This principal applies similarly to the management of soil P release to leachate because topsoil generally serves as the primary source of leachate P that has moved by preferential flow along macropores (Addiscott and Thomas 2000). Thus, in the Oklahoma field study of Sharpley and Smith (1994), described above, the implementation of no-till management in wheat that was formerly tilled significantly increased dissolved P concentrations in runoff (Fig. 4), but decreased overall P losses. Compared with tilled watersheds, this decrease was a function of (a) a dramatic reduction in erosion (95%) and associated sediment-bound P (85%) and (b) lower runoff volumes brought by greater infiltration via macropore flow under no-till (Sharpley and Smith 1994). As a consequence of greater infiltration, nitrate leaching potential increased with concentrations rising from 0.4 to 6.7 mg L^{-1} in 4 yr after conversion from conventional to no-till wheat. Clearly, soil management to mitigate P losses should consider N mobility, so as to eliminate indirect consequences that may negatively impact overall water quality. Similarly, although no

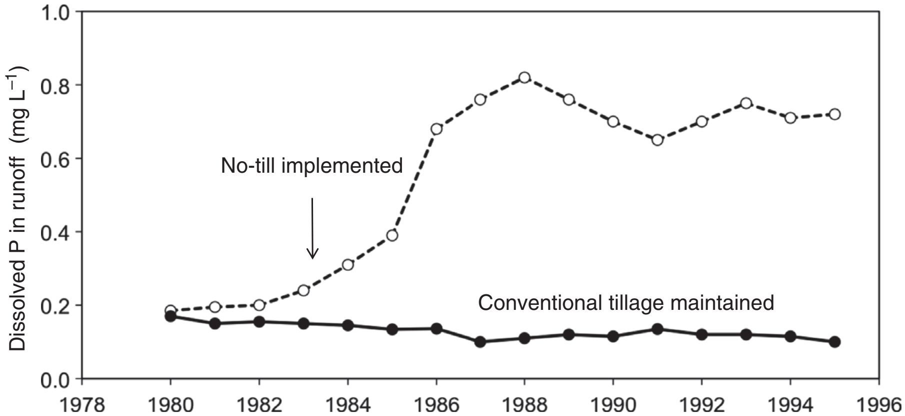


Fig. 4. Average annual dissolved P concentrations in runoff from two wheat fields in Oklahoma, US. Both were tilled until 1984, when one was converted to no-till. Adapted from Sharpley and Smith (1994).

causal link has yet been definitively established, dissolved P concentrations have been increasing in discharge from the LEASEQ watersheds since the mid-1990s, coincident with the widespread adoption of no-till cropping practices (Richards 2009).

Even with the use of short-term approaches such as tillage management to invert or mix soils and mitigate dissolved P losses in runoff, more significant reductions in dissolved P runoff may be hampered by the persistence of legacy P in soils with a long history of manure and fertilizer application above crop removal. For example, a study by McCollum (1991) estimated that up to 18 yr of no further P application with continuous cropping of corn and soybeans would be required to reduce Mehlich-3 P concentrations from 100 mg kg^{-1} to the agronomic threshold of 20 mg kg^{-1} on a sandy coastal plain soil in North Carolina. More recently, an experiment was conducted at a site on the Atlantic Coastal Plain of Maryland to evaluate the effects of three different P application scenarios (N-based application, P-based application, no P applied) on long-term trends in Mehlich-3 P concentrations in soil (Sharpley et al. 2009). After 10 yr of monitoring, no difference in Mehlich-3 P was detected between the three treatments (Fig. 5), thus corroborating the findings of McCollum (1991) and further demonstrating the long-term challenges in reducing the effects of legacy P in soils on continued release of P to surface and subsurface water flows. At badly overloaded legacy P sites, more aggressive management strategies, such as the application of chemical amendments (e.g., alum, gypsum, ferrihydrite) to lessen surface soil P solubility (Callahan et al. 2002; Rhoton and Bigham 2005) or the installation of runoff-intercepting filters to trap dissolved P (Penn et al. 2007), may be required.

THE OVERWHELMING INFLUENCE OF HYDROLOGY

A widespread hypothesis is that the majority of P exported from a watershed derives from relatively minor areas within the watershed (e.g., Gburek and Sharpley 1998). These areas, termed "critical source areas" are defined as zones within a watershed where elevated concentrations of P coincide with hydrologic flow pathways that readily transfer the P to runoff. This concept highlights the spatial and temporal variability in P sources within a watershed as well as the spatial and temporal variability in hydrologic processes. Modern site assessment indices depend, at most, upon our ability to adequately represent the spatial and temporal variability in hydrologic pathways that convert P in field soils into surface water contaminants and, at least, upon our ability to determine the hydrologic connectivity of a field to surface water.

Much of the literature documenting hydrologic controls of critical sources areas has focused on watersheds where variable source area hydrology (Ward 1984) predominates. Variable source area hydrology is remarkably widespread, supported by discontinuous features in a landscape that result in spatial differences in soil moisture, including relatively impervious features that promote lateral (as opposed to vertical) movement of water. These features may be related to different depths or strata of bedrock along a landscape, or to the expression of pedogenic features with low permeability (e.g., pans, textural contrasts). Variability in antecedent soil moisture and surface runoff generation within such landscapes may be profound, producing pathways of flow that are able to convert modest sources of P into significant critical source areas.

A few recent studies have examined the role of contrasting runoff processes in P losses. For example, Srinivasan and McDowell (2009) and McDowell and Srinivasan (2009) examined the differential roles of infiltration-excess (runoff generated by rain storm characteristics relative to infiltration properties of soil) and saturation-excess (runoff generated by antecedent moisture saturation of soil) processes in P losses from grazed grassland watersheds in New Zealand. They found that the infiltration excess runoff producing areas

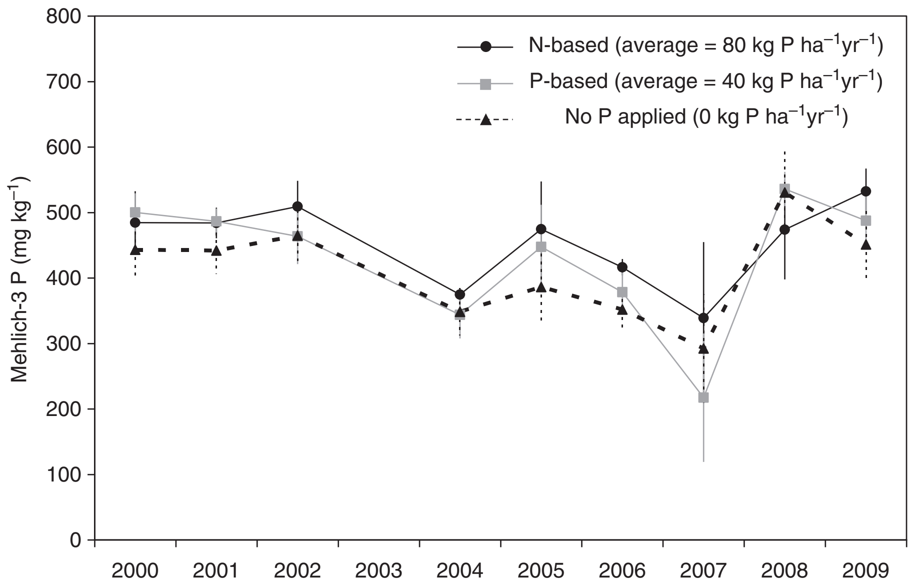


Fig. 5. Effects of three different poultry litter application strategies (0, 40 and 80 kg total P ha^{-1} yr^{-1}) on long-term Mehlich-3 soil P, Maryland, USA.

formed as a result of farm infrastructure (e.g., lanes), or created by animal treading and soil compaction (e.g., stock camps or around watering troughs and gateways), caused most of the losses of dissolved P in small storms that dominated during summer and fall (Fig. 6). Those P losses were particularly important since they coincided with the period when dissolved P would be most detrimental to stream water quality. In contrast, during the New Zealand winter, when losses were of lesser importance to water quality, most P was lost from areas prone to saturation-excess runoff.

Surface runoff generation from the shale and sandstone agricultural landscapes of Appalachia's Ridge and Valley Province typifies variable source area hydrology. Buda et al. (2009) monitored surface runoff within a strip-cropped watershed in which high concentrations of Mehlich-3 soil P (177 mg kg^{-1}) were found in association with upper landscape positions (at least

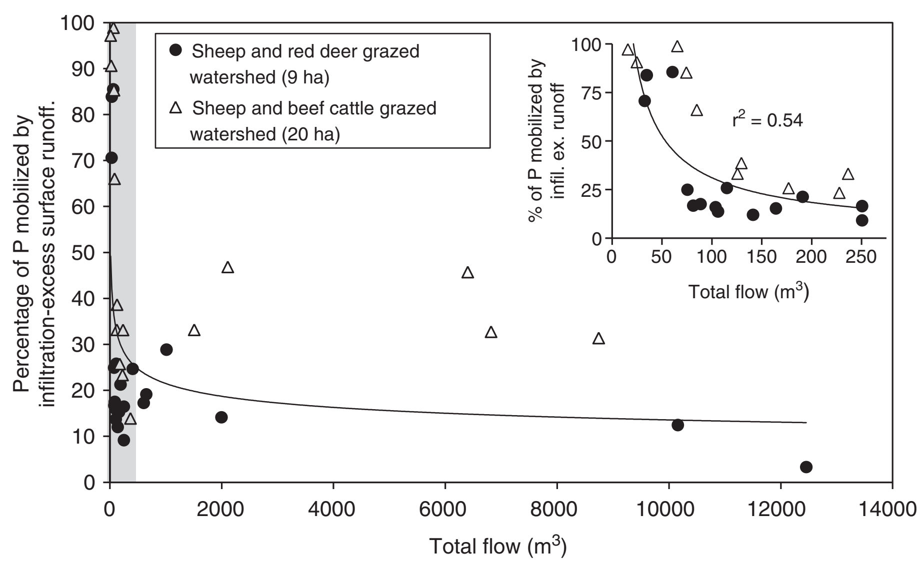


Fig. 6. The contribution of dissolved P load collected from infiltration-excess surface runoff to total dissolved P loads during storms of different sizes. The grey box represents the area where 90% of the summer and fall storms occurred. Data from McDowell and Srinivasan (2009).

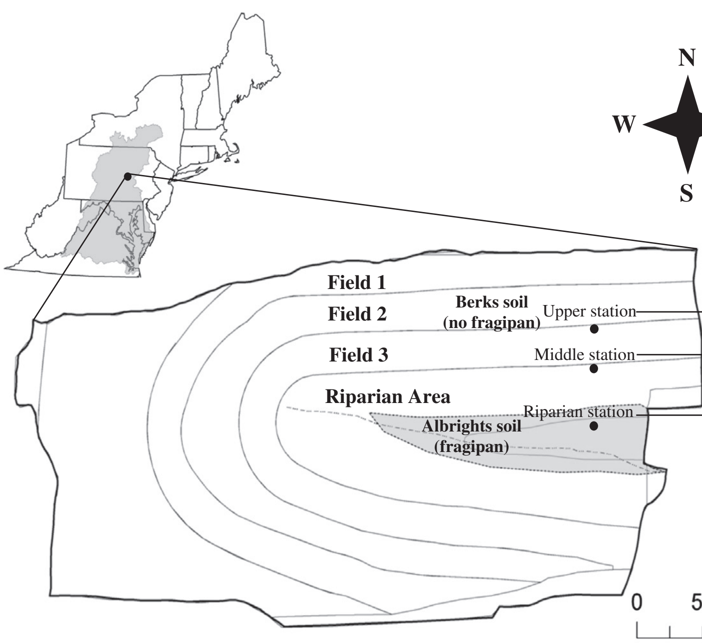
three times the agronomic optimum; i.e., 30–50 mg kg^{-1}), while lower concentrations of Mehlich-3 soil P, roughly at agronomic optimum, were found in the riparian area (i.e., 72 mg kg^{-1}; Fig. 7). Riparian soils possessed a fragipan and were prone to water logging, resulting in saturation excess runoff volumes that were more than 46-fold greater than infiltration excess runoff volumes derived from upper landscape positions. Furthermore, 27% of infiltration excess runoff from upper landscape positions reinfiltrated prior to reaching lower landscape positions, and therefore lacked the connectivity with the watershed's stream channel that was observed with the saturation excess runoff from the riparian area.

Dissolved P concentrations in runoff from the various soils related well to their Mehlich-3 soil P content ($r^2 = 0.89$), consistent with the trend in Fig. 3 [adapted from Buda et al. (2009)]. The riparian area was managed as a grassed buffer and did not receive current applications of P, an appropriate management practice to minimize P transfers from hydrologically active soil. Soils at upper positions were maintained in row crops, receiving regular additions of fertilizers, even manures. Due to differences in runoff generation, P losses from the riparian buffer were approximately 8 kg total P ha^{-1} annually, a concern in any landscape, whereas losses from the upslope cropped fields were <1 kg total P ha^{-1}. The elevated losses of P from the riparian area were a legacy of historical applications of P to soils that were prone to runoff.

Identifying critical source areas like the riparian area in Buda et al. (2009) is extremely difficult, given that variability in runoff flows from the hillslope, not variability in P sources, was primarily responsible for differences in P loads between fields. The overwhelming role of hydrology in activating a modest source of legacy P highlights the inherent difficulty in relying on soil P thresholds alone to define the risk of dissolved P loss to runoff. Clearly, P site assessment tools to target remedial action must be equipped to accurately and precisely identify hydrologic potential. As described above, remedial options for legacy P sources do exist, from field amendments to engineered runoff filters, but these options generally require aggressive action not seen in most agricultural operations.

CONCLUSION

The role of soils in agricultural P transfers involves hydrologic and chemical processes and interactions between them that determine how effective individual management practices are in mitigating P losses. Undoubtedly, control of sediment-bound P losses must remain the dominant conservation priority of Great Lakes area P management strategies, but trends in dissolved P loads from certain tributaries point to the need for other soil P management strategies. Modern soil P management centers around the dilemma that soils and sediments that once served as sinks of P may also act as sources, despite having low soil P concentrations.



	Mehlich-3 P ($mg\ kg^{-1}$)	Mean annual total P loss ($kg\ ha^{-1}$)	Runoff Volume, 2002-2004 (L)
Upper station	177	<1	32
Middle station	144	1	66
Riparian station	72	8	4539

Fig. 7. Map of 11 ha Mattern Watershed in Pennsylvania, USA, a subwatershed of the Susquehanna River Basin, showing boundaries for fields and soils, as well as the location of runoff monitoring stations. Surface runoff was continuously monitored from 2002 to 2004. Mechlich-3 soil P immediately above each runoff monitoring location, total annual P loss in runoff and runoff volume, are presented in the table.

Empirical ties between dissolved P in runoff and soil tests can be used to set soil P thresholds to guide P amendments, but how does one manage hydrologically active soils that readily desorb P to runoff? Or, in the case of no-till soils, do we adequately understand the trade-offs between periodically tilling surface horizons to recharge sorption sites within the effective depth of interaction between runoff and soil, to tillage-induced erosion of particulate P? Ultimately, plans for controlling P transfers from agricultural soils will need to provide tactical guidance to deal with the complex interactions of hydrology and soil management.

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