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A Conceptual Approach for Integrating Phosphorus and Nitrogen Management at Watershed Scales

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ABSTRACT

Since the late 1960s, point-sources of water pollution have been reduced due to their ease of identification and treatment. As water quality problems remain and further point-source measures become less cost-effective, attention is directed toward reducing agricultural nonpoint-sources of P and N. In the past, separate strategies for P and N were developed and implemented at farm or watershed scales. Because of differing biology, chemistry, and flow pathways of P and N in soil, these narrowly targeted strategies may lead to mixed results. In some cases, N management of manures has increased soil P and subsequent P enrichment of surface runoff, while no-till has reduced P losses but increased nitrate leaching. Thus, an integrated approach to nutrient management is needed, with best management practices (BMPs) targeted to critical areas of a watershed that contribute most of the P and N exported. We have developed indices that identify critical sources and transport pathways controlling P and N export. These indices are applied to a mixed land use watershed in Pennsylvania. Areas most vulnerable to P loss are limited to small, well-defined areas of the watershed (<20% of area) near the stream channel. In contrast to P, larger areas contribute to nitrate leaching and generally occur on the upper boundaries of the watershed (60%), where freely draining soils and high manure and fertilizer N applications are made. Thus, differing levels of nutrient management may be appropriate for different areas of a watershed.

MANAGING agricultural sources of P and N at the watershed scale in order to reduce their impact on water quality requires a balanced and holistic approach. In the past, most emphasis has been placed on N management to ameliorate nitrate losses to ground water. While the high solubility and mobility of nitrate within agricultural systems may justify this emphasis, such bias ignores other critical elements, notably P.

Now that most point-source inputs of P to freshwaters are being addressed, the spotlight has shifted back to nonpoint, largely agricultural P sources, to explain the continuing eutrophication of many rivers and lakes in Europe and the USA. This shift in emphasis has generated research that demonstrates a greater risk of P loss from agricultural land than previously thought (Heathwaite et al., 1999; Sharpley et al., 1998).

In this paper we review first the impact of agricultural land management on P and N losses. Second, we evaluate the need for *integrated* N and P management at the watershed scale to incorporate the spatial variation in nutrient loss risk within a watershed. Finally, we explore the use of simple P and N indexing systems to help delineate risk areas and focus on watershed management through the design of appropriate BMPs.

THE PROBLEM

Much of the recent focus on P loss from agricultural land has arisen through concern over regional and national imbalances in agricultural inputs and outputs of P. The rapid growth and intensification of the livestock industry in certain areas of the USA and Europe is one source of the problem (Kronvang and Svendsen, 1991; Sharpley et al., 1998; Valpasvuo-Jaatinen et al., 1997). The intensification has created a P surplus (P input in feed and fertilizer minus P output in produce) in these areas, as feed and livestock are produced in geographically separate areas where it is uneconomical to recycle livestock waste back to feed-producing land (National Research Council, 1993; Sharpley and Withers, 1994).

Part of the problem is that recommended manure application rates are routinely based on their N content and crop N requirement to minimize the purchase of commercial N fertilizer and risk of nitrate leaching. The bias to N has resulted in more P being applied in manure (N/P ratio of 2:1 to 6:1) than taken up by crops (N/P ratio of 7:1 to 11:1) (Eck and Stewart, 1995). The N/P imbalance is exacerbated by N volatilization from manure and the slow mineralization of N from the organic fraction. This has led to an increase in the concentration of P in some soils and subsequent risk of P transport to drainage waters (Sharpley et al., 1996, 1998).

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Abbreviations: BMP, best management practice; CSA, critical source area; DP, dissolved phosphorus; NSA, nitrate sensitive areas; PP, particulate phosphorus; TN, total nitrogen; TP, total phosphorus; VSA, variable source area.

CRITICAL PATHWAYS OF PHOSPHORUS AND NITROGEN TRANSPORT

Phosphorus and N mobilization from agricultural nonpoint-sources depends on the coincidence of *source* (soil, crop, and management) and *transport* (runoff, erosion, and channel processes) factors. Source control factors relate to watershed areas that have a high potential to contribute nutrients. For P, source areas are often spatially confined and limited in extent, generally reflecting soil P status and P inputs (Gburek and Sharpley, 1998; Pionke et al., 1997). For N, amounts applied in excess of crop requirements can be leached from the soil profile in percolating water.

Attempts to manage P source areas using soil test P recommendations alone to guide fertilizer and manure applications have not always accomplished the desired or expected P loss reductions (Daniel et al., 1994; Sharpley and Rekolainen, 1997). This is primarily because this approach does not consider transport controls on P loss.

At the watershed scale, P and N have differing contributing areas where source and transport factors coincide to initiate nutrient mobilization. Transport factors are more limiting for P relative to N, because the high mobility of N as nitrate in leaching water means that virtually all the nitrate created by source factors is translated into N loss. For P, both surface and subsurface pathways of P loss exist. Surface runoff is generally viewed as the dominant pathway of loss, particularly in cultivated watersheds such as the one described in this paper. Only certain spatially confined areas of a watershed contribute surface runoff (transport control) and P mobilization does not occur unless such areas *coincide* with land of high P potential (source control) (Gburek et al., 1996, 2000; Pionke et al., 1997; Pote et al., 1996).

The P content of water percolating through the soil profile is generally lower than for surface runoff, and typically will decrease as the degree of soil–water contact increases due to P sorption by P-deficient subsoil. While this generalization is true for matrix flow through soils, recent research suggests that macropore, or bypass flow, together with P transport in artificial drains, may increase P loss (Dils and Heathwaite, 1996; Sims et al., 1998). Currently, the P index described below does not account for P losses in subsurface flow. Although it is possible to conceptually devise such an index, more research on subsurface P losses at watershed scales is required to ascertain their importance relative to surface runoff (Heathwaite et al., 1999).

COMPROMISING WATER QUALITY: BALANCING NUTRIENT MANAGEMENT

Owing to the differing chemistries and flow pathways of P and N, remedial efforts directed to either P or N *individually* can negatively impact the other nutrient. Similarly, addressing nutrient loss by treating source and transport factors separately will limit the effectiveness of remedial measures (Sharpley et al., 1994). For N, remedial strategies may be applied to the whole watershed. For P, management strategies will reduce P export most effectively when targeted to the critical source areas within a watershed most vulnerable to P loss in surface runoff and erosion (Heathwaite and Johnes, 1996; Heatwole et al., 1987; Prato and Wu, 1991). For example, basing manure application on crop N requirements to minimize nitrate leaching to ground water may increase soil P and enhance P loss in surface runoff. By contrast, artificial drainage may reduce PP and DP losses by reducing the magnitude of surface runoff, but N leaching may be enhanced (Turtola and Paajanen, 1995). Recent advances have been made. For example, the UK manure application recommendations contained in the Ministry of Agriculture, Fisheries and Food Code of Good Agricultural Practice (Ministry of Agriculture, Fisheries and Food, 1998), contain specific reference to the need to avoid accumulation of P through manure applications on soil where existing levels are in excess of those required for optimum crop production. However, such recommendations are guidelines only and are not enforced in legislation.

The interrelationship between P and N loss from agricultural soils may be illustrated using cultivation practice as an example. In the USA, no-till is commonly recommended as a conservation measure to reduce erosion. Figure 1 shows TP and DP loss in surface runoff from conventional tillage wheat vs. no-till wheat for 2 ha field-scale experiments in Oklahoma. Total P loss in surface runoff was reduced by 70% (Fig. 1) and total N loss by 75% (data not shown). Thus, for total nutrient losses this management option is successful. However, it is important to consider the nutrient fractionation. Figure 1 shows that while conversion to no-till decreased TP loss in surface runoff, it increased DP and nitrate

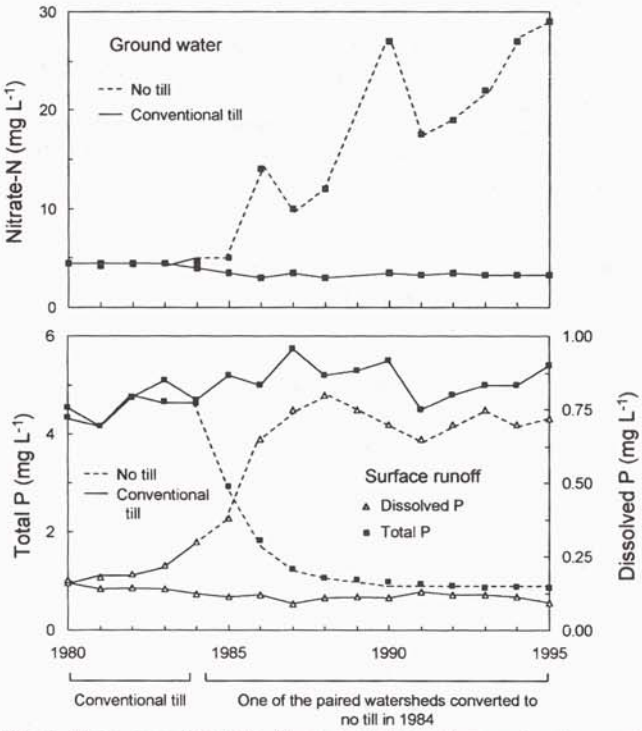

Fig. 1. Mean annual nitrate N concentration of ground water, and dissolved and total P concentration in surface runoff, as a function of tillage management of watersheds in Oklahoma (data adapted from Sharpley and Smith, 1994).

losses. Thus, nitrate N concentration in ground water increased from 4.5 to 29 mg L^{-1} and DP loss increased by 300% (Sharpley and Smith, 1994). The increase in nitrate leaching may be attributed in part to 33% more infiltration of rainfall water at the expense of surface runoff under no-till compared with conventional-till wheat. In fact, no-till decreased surface runoff volume and erosion 95% (Sharpley and Smith et al., 1994). The increase in DP concentration in surface runoff can be attributed to leaching of P from crop residue material and preferential transport of enriched clay-sized particles under no-till compared with conventional tillage practices.

Similarly, Yli-Halla et al. (1995) report that erosion control measures designed to reduce TP loads do not necessarily reduce eutrophication, because DP losses through leaching may remain high. Also, Mostaghimi et al. (1988) report no significant change in losses of DP between conventional and no-till cultivation. Thus, managing land use to control nutrient mobilization is not straightforward. The fractionation of nutrient forms and pathways of loss may be detrimentally altered. The bioavailability of P transported as a result of certain management practices may continue to impact the trophic status of receiving waters despite decreased TP loss.

The positive and negative impacts of land management on resultant water quality need to be considered in the development of remedial measures. Clearly, a technically sound framework should be developed that includes critical sources of P and N export from agricultural watersheds. This is necessary so that optimal strategies at farm and watershed scales can be implemented to best manage both P and N. Here we evaluate indices designed to quantify the risk of P and N loss from agricultural fields. The indexing system provides a measure of the spatial variation in P and N loss risk at the watershed scale. From this we demonstrate how source and transport factors operate differently for P and N. By integrating P and N management rather than addressing each independently, BMPs should result that avoid compromising water quality remediation.

CONCEPTUAL APPROACH: CRITICAL SOURCE AREAS OF PHOSPHORUS AND NITROGEN LOSS

The spatially and temporally dynamic CSAs controlling P loss reflect the coincidence of source and transport factors. Several studies report the importance of CSAs in defining P loss risk. For example, Pionke et al. (1997) showed that up to 90% of annual P loss comes from <10% of the land area in hill-land watersheds. Even in regions where subsurface flow pathways dominate, areas contributing P to drainage waters appear to be localized to soils with high soil P saturation and hydraulic connectivity to the drainage network. For example, Schoumans and Breeuwsma (1997) found that soils with high P saturation contributed only 40% of TP load, while a further 40% came from areas where the soils have only moderate P saturation but some degree of hydraulic connectivity with the drainage network.

The original P index described by Lemunyon and

Table 1. The modified P indexing system to rate the potential P loss in runoff from site characteristics (from Gburek et al., 1998).

	Phosphorus transport potential (value)				
Factor (wt.)	None (0.6)	Low (0.7)	Medium (0.8)	High (0.9)	Very High (1.0)
Soil erosion (1.0)†	Negligible	<10	10–20	20–30	>30
Irrigation erosion (1.0)	Negligible	Infrequent irrigation on well-drained soils	Moderate irrigation on soils with slopes <5%	Frequent irrigation on soils with slopes of 2 to 5%	Frequent irrigation on soil with slopes >5%
Runoff class (1.0)	Negligible	Very low or low	Medium	High	Very high
Contributing distance, m (1.0) [return period, years]	None (0.2) >170 [>10]	Low (0.4) 170–130 [10–6]	Medium (0.6) 130–80 [5–3]	High (0.8) 80–30 [2–1]	Very High (1.0) <30 [<1]
	Phosphorus source potential (value)				
	None (0)	Low (1)	Medium (2)	High (4)	Very High (8)
Soil test P (1.0)‡	<10	10–30	30–100	100–200	>200
Fertilizer P rate (0.75)¶	None applied	1–15	16–45	46–75	>75
Application method for fertilizer (1.0)	None	Placed with planter or injected deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 mo or surface applied <3 mo before crop	Surface applied >3 mo before crop
Organic P rate (0.5)¶	None applied	1–15	16–30	30–45	>45
Application method for organic source (1.0)	None	Placed with planter or injected deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 mo or surface applied <3 mo before crop	Surface applied >3 mo before crop

† Units for soil erosion are Mg ha^{-1}.
‡ Units for Mehlich-3 soil P are mg P kg^{-1}.
¶ Units for P application are kg P ha^{-1}.

P index rating = (Erosion rating × Runoff rating × Return period rating) × Σ (Source characteristic rating × Weight)

Site vulnerability	Total index rating value
Low	<5
Medium	5–9
High	10–22
Very High	>22

Gilbert (1993) accounts for and ranks transport (runoff and erosion) and source (soil P, applied P type, rate, and method) factors controlling P loss in surface runoff. Gburek et al. (2000) modified the original P index to more accurately represent the surface runoff–soil P relationship and potential for surface runoff to contribute to streamflow via CSAs. The modified P index is used in this paper and Table 1 summarizes the P index criteria.

Nitrogen loss from agricultural land generally occurs on a watershed-wide scale (Heathwaite et al., 1989). This is essentially because movement of water is translated into movement of nitrate (Kissel et al., 1982). The magnitude of N loss depends on the amount of nitrate in the soil (source control). The rate of N loss through leaching (transport control) depends on soil properties (primarily texture and permeability), and the amount of water percolating through the soil profile (rainfall, irrigation). Usually, high soil nitrate concentrations imply a high N leaching potential. For cropland, the balance between crop input and uptake (residual soil N) and the nature of N inputs (fertilizers/manures) are important. Some N leaching will occur irrespective of the magnitude of N inputs due to N mineralization. Thus, leaching of mineralized N may be high where plant uptake of N is low towards the end of the growing season. Similarly, some land uses, such as grazed grassland, recycle manure N back to the land surface, where it may be mobilized in surface or subsurface flow. Excess N will be available for leaching and may impact nitrate concentrations in ground water.

Using the same format as the P index, the N index (Table 2) integrates source and transport factors to characterize site vulnerability to N loss in leaching. The index determines the amount of nitrate leached from agricultural soils in terms of soil properties, the amount of water draining through the soil and the amount of nitrate in the soil. The N index is modified from research on the N leaching classes for Kansas soils (Kissel et al., 1982). Source factors for N (fertilizer N, manure N, and application method) are weighted, and as with the modified P index, source and transport factors are multiplied to achieve the final weighting. Thus, the final N index value for each site is the sum of the weighted values of all source factors multiplied by the transport factors (Table 2). The current version of the N index is applicable to humid regions, in arid or semiarid areas, percolation may be limited and ground water recharge contributes to a smaller portion of total watershed runoff.

APPLICATION OF PHOSPHORUS AND NITROGEN LOSS RISK INDICES

We used a subwatershed in the Chesapeake Bay Basin, PA, to apply the P and N index approaches. The criteria in both indices (Tables 1 and 2) were applied to all fields in the study watershed in order to identify areas of high and low risk for P and N loss (Fig. 2). The site is described in detail in Gburek and Sharpley (1998) and Gburek et al. (2000). The 40 ha FD-36 subwatershed has soil P data (0- to 5-cm depth) available on a 30-m grid over the watershed, together with a digital elevation model (DEM), stream water quality data from 1996, and information on land use and fertilizer inputs on a field by field basis.

Transport Controls on Phosphorus and Nitrogen Loss

The differences in transport factors for P and N loss are compared in Fig. 3. The maps were generated from Geographic Information System (GIS) images using IDRISI and SURFER software. For P, the width of the near-stream zone producing surface runoff was esti-

Table 2. The N index to rate the potential loss in leaching from site characteristics determining source and transport factors.

	Leaching potential from transport factors (value)				
Factors	**None (0)**	**Low (1)**	**Medium (2)**	**High (4)**	**Very High (8)**
Texture	Clay	Clay loam to silty clay loam	Loam to silt loam	Loamy fine sand to coarse sandy loam	Sand
Permeability†	<1.5	1.6–4	4.1–14.9	15–50	>50
	Leaching potential from source factors (value)				
Fertilizer N rate‡	None applied	1–50	51–150	151–300	>300
Application method for fertilizer	None	Placed with planting	Incorporated immediately before crop	Surface-applied >3 mo before crop or incorporated <3 mo before crop	Incorporated >3 mo before crop
Manure N rate‡	None applied	1–50	51–150	151–300	>300
Application method for manure	None	Placed with planting	Incorporated immediately before crop	Surface applied >3 mo before crop or incorporated <3 mo before crop	Incorporated >3 mo before crop

† Units for permeability are cm h^{-1}.
‡ Units for N application are kg N ha^{-1}.

N index rating = (Texture rating × Permeability rating) × Σ (Source characteristic rating × Weight)

Site vulnerability	Total index rating value
Low	<3
Medium	3–8
High	9–18
Very High	>18

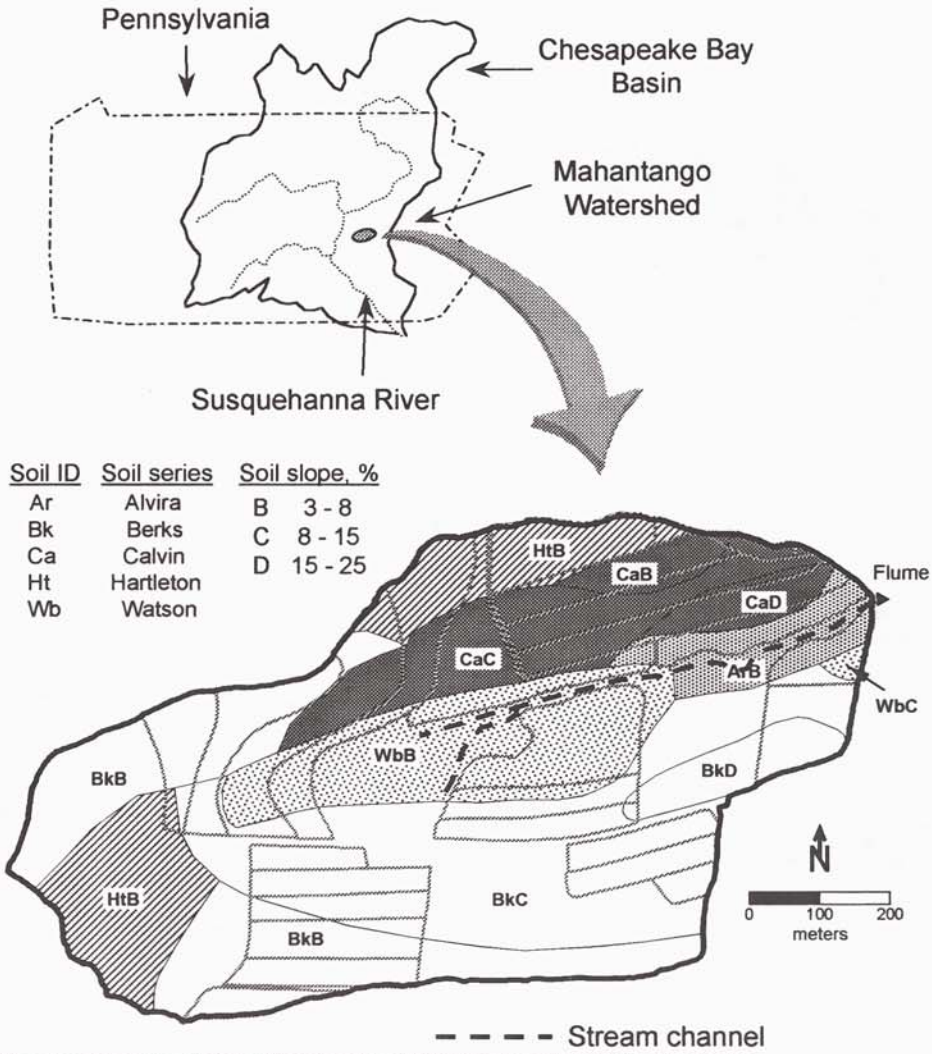

Fig. 2. Location, soil type and field boundaries of subwatershed FD-36 in the Chesapeake Bay Basin.

mated using the approach described in Gburek et al. (2000). The contributing area function produces a distinct zonation of P loss because the risk of surface runoff decreases with increasing distance from the stream (Fig. 3). The zonation shown reflects the spatial variation in saturation-excess surface runoff, where a rising stream water level in response to stormflow results interacts with a rising water table in near-stream zones, thus initiating P transport in surface runoff. Initiation of surface runoff from areas some distance from the stream requires large magnitude storms that have a long return period, hence the probability of surface runoff generation is low in such areas. Furthermore, work by Gburek et al. (2000) in the study watershed demonstrated most P loss could be accounted for by near-stream VSAs. The specific zonation shown does not account for other forms of VSA, which may be important in other study watersheds (e.g., where surface runoff is triggered as the soil becomes saturated via lateral percolation above an impeding horizon, or where the soil water table rises to the ground surface through convergent flow into hillslope hollows) (Beven and Wood, 1983; Heathwaite et al., 1999). Such zones are highly dependent on watershed topography and flow routing. Their importance for P loss at the watershed scale relative to losses in surface runoff has yet to be clearly demonstrated (Heathwaite et al., 1999).

The distribution of N leaching potential differs because the contributing area encompasses a larger watershed area (Fig. 3). Furthermore, the location of high N transport risk occurs on the watershed boundaries rather than in near-stream zones, as for P. Nitrogen transport risk closely corresponds with the permeability of the watershed soils. In humid climates, high soil permeability correlates with a high potential for N leaching. In the study watershed, areas of high leaching potential occupy the watershed interfluves. By contrast to P, near-stream zones have a low vulnerability to nitrate loss because the soils there have a higher clay content, low permeability, and hence are discharge zones during most events.

Integrating Source and Transport Controls on Phosphorus and Nitrogen Loss

The P and N index systems utilize the transport factors shown in Fig. 3 for P and N, respectively, and combine these with source factors of land use and management to reflect P and N loss potential within the watershed. For both P and N, source and transport factors are multiplied rather than added, as in the original P index.

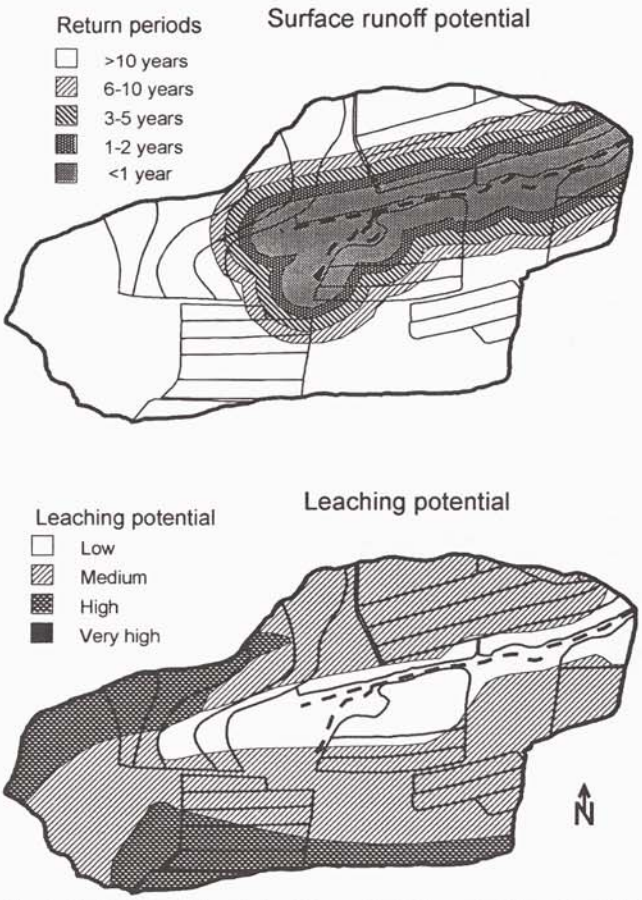

Fig. 3. Surface runoff and leaching potentials controlling P and N transport, respectively, from watershed FD-36.

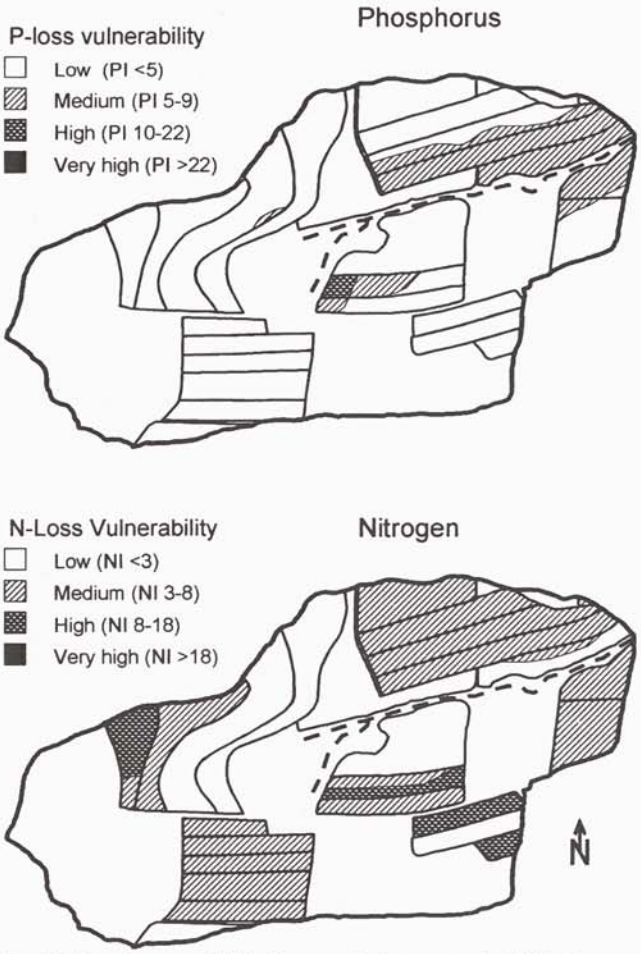

Fig. 4. Phosphorus and N indices applied to watershed FD-36.

The multiplicative index systems allow transport factors to be correctly weighted (Gburek et al., 2000). Thus, the risk of P or N loss is high only if both source and transport factors coincide. This avoids previous problems of some watershed areas appearing to have a high risk of P loss, while their location, relative to the stream network, meant that this potential was rarely translated into loss. Johnes and Heathwaite (1997) also used a distance-decay function to model the impact of land use change on P and N concentrations in streams draining the Slapton Watershed, southwest England. They argued that nutrient-contributing areas greater than 50 m from the drainage network were less important than near-stream zones due to attenuation and uptake of nutrients during downslope transit.

The spatial variation in P and N loss estimated risk using the index system is shown in Fig. 4. Here it is clear that P loss risk is confined to a few key areas of the watershed, which form critical source areas of P loss. There are no *very high* zones of P loss (Table 1); zones of *high* P loss account for <1% of the watershed area, with *medium* risk areas accounting for 17% of the watershed. Medium and high P loss zones are largely, but not wholly, in near-stream zones. Phosphorus risk zones some distance from the stream occur where very high source factors (e.g., land receiving high levels of animal manures) coincide with a moderate transport risk. Not all near-stream zones are highlighted as areas of high P loss risk because the high water table in many of these areas means that it is relatively low-grade land and as such receives much lower fertilizer and manure inputs than other watershed areas.

Much larger watershed areas are susceptible to N than P loss. Thus, 60% of the watershed has medium to high vulnerability to N loss (Fig. 4). No land falls into the very high category. The N loss weighting reflects the greater mobility, and hence higher risk of transport (Fig. 3), although this transport risk must be combined with N source areas to produce the overall risk pattern shown in Fig. 4. Critical source areas for N are both less well defined and less important relative to P; some *hotspots* showing high vulnerability to nitrate loss are apparent. These localized areas tend to coincide with fields where manure inputs are high and N enrichment enhances the potential for N loss.

WATERSHED MANAGEMENT TO CONTROL PHOSPHORUS AND NITROGEN LOSS USING AN INTEGRATED APPROACH

In general, intensive agriculture enhances N loss through leaching to ground water and P loss in surface runoff on an area basis, though not necessarily per unit of crop yield (Dilz, 1988; Sharpley et al., 1994). Reviewing global trends in P and N concentrations in freshwaters, Heathwaite et al. (1996) found that the increase in P concentrations paralleled trends observed for N

during the past 50 yr. Greater P and N inputs to agricultural watersheds were identified as the causal factor in the trends of increasing nutrient concentrations in surface waters. Integrated nutrient management is necessary to reverse or at least stabilize these trends. However, setting standards for P is less clearcut than for N, where health risks prompted action and a maximum contaminant level for nitrate in drinking water was set at 10 mg L^{-1} (USEPA, 1986). Critical P concentrations for eutrophication control (0.01–0.02 mg L^{-1}) are an order of magnitude *lower* than those in soil for crop growth (0.20–0.30 mg L^{-1}), thus demonstrating the sensitivity of surface waters to P loss from agricultural sources.

An Integrated Phosphorus and Nitrogen Index

It is clear that P and N have different critical source areas and pathways of loss (Heathwaite et al., 1996). The spatial delineation of watershed areas contributing P relative to N suggests that a management framework should begin by assessing site vulnerability to P loss. For P, management of both source and transport factors includes modifying fertilizer and manure applications, and implementing measures designed to minimize the incidence of surface runoff. For N, management of source factors, such as N inputs and crop selection and rotation, will be most effective because transport factors will be difficult to modify in humid climates. The BMPs need to be flexible to enable differential nutrient management over the watershed and avoid compromised water quality remediation. Flexibility may be achieved by shifting the focus towards integrated approaches of P and N management that have an environmentally-sound basis rather than addressing each nutrient separately.

The degree of bias toward P or N would depend on whether nutrient management objectives are being devised for P control or N control. In some eastern U.S. states, for example, legislation has been introduced to base manure inputs to land on P rather than N (Sims and Sharpley, 1998). Similarly, in the UK, the European Union Nitrate Directive and schemes such as the NSAs (Ministry of Agriculture, Fisheries and Food, 1989a, b) enforce bias toward N management in nutrient management programs. Unfortunately such *blanket* legislation may override considerations of watershed characteristics (e.g., soil permeability, soil P concentration, land use practices) that determine the dominant pathways of nutrient transport and the likelihood of P or N loss. The P and N index systems described earlier are valuable here because they incorporate these critical watershed criteria within the index (Tables 1 and 2). Using a simple format, the index systems enable evaluation and comparison of the risk of P and N loss. By comparing the distribution of the calculated classes of risk from *very high* to *low* (Tables 1 and 2) within the study watershed it is possible to delineate key areas of P and N loss and devise appropriate nutrient management programs to account for this variation. For example, if the potential for nitrate leaching exists for land receiving manure applications, N should be the priority management consideration. Conversely, where watershed areas have a high potential for surface runoff and erosion, or where the risk of P loss in artificial drainage is high, P should receive primary consideration (Sharpley et al., 1998). It is also important to direct the focus of any integrated nutrient management program to the water quality objectives for the receiving waters. The focus on P and/or N may depend on the sensitivity of the receiving waters to N or P limitation.

Management of Source Control Factors

In the USA, recent nutrient management programs have sought to establish general threshold P concentrations in an attempt to minimize soil P buildup. Designation of a most appropriate threshold soil P concentration is widely disputed. Without recourse to the hydrological criteria that govern whether potentially mobile P is translated into actual P loss, such *blanket* programs are likely to prove unnecessarily restrictive. Furthermore, where legislative controls have been introduced for P control (e.g., Maryland), little evaluation has been made of their potential impact on N. Because legislation is focused on reducing P application to land from livestock slurries and manures, it is that likely crop requirements for N will have to be supplemented by mineral fertilizer.

While strategies to control P sources are in their infancy, those for N management are well established. However, there has been little consideration of the impact of N management on P loss. For example, the introduction of NSAs in the UK (Ministry of Agriculture, Fisheries and Food, 1989a) was aimed at minimizing the risk of nitrate leaching, using source management such as cover crops in autumn. While N controls are critical in recharge areas it is not clear what impact they have in surface runoff areas of a watershed, and by inference what impact they have on P loss. Cover crops would reduce the risk of surface runoff, which may be beneficial for TP control, but subsurface losses of DP may be enhanced. Unger et al. (1998) showed that cover crops reduce surface runoff by up to 50% due to increased infiltration. Similar reduction in TN (80%) and TP (71%) were recorded due to vegetative protection, but the impact on the bioavailable fractions, nitrate (61% reduction), and DP (37% reduction) was less pronounced.

A further example is the European Union Nitrate Directive (Heathwaite et al., 1993). This directive controls the timing of manure application with regard to N but makes no evaluation of the impact on P. Few studies have evaluated integrated P and N management strategies. An exception is Johnes and Heathwaite (1997), who used an export coefficient model to examine the impact of watershed-scale P and N management strategies in reducing the nutrient loading to surface waters. They examined a range of nutrient source management options at the watershed scale, including reductions in fertilizer application rates and implementation of the basic NSA scheme. They predicted that the greatest reduction in P and N inputs to receiving waters was achieved by reducing P and N loss from near-stream zones (<50 m from the stream channel). This option involved conversion of near-stream land to ungrazed, unfertilized grassland, coupled

with a 75% reduction in livestock density in the watershed as a whole.

Management of Transport Control Factors

Phosphorus transport generally occurs in surface pathways from well-defined areas of a watershed, so there is scope for management of transport factors. For N, the dominance of subsurface pathways of N transport precludes active management to a large extent in humid climates. Surface runoff mobilizes sediment together with nutrients originally applied as fertilizer and/or manure. Hence, any feature that slows surface runoff and/or encourages infiltration or sediment trapping may reduce nutrient loss in surface runoff. Such measures include terracing, contour tillage, cover crops, buffer strips, riparian zones, and impoundments or small reservoirs (Bingham et al., 1980; Gale et al., 1994; Muscutt et al., 1993). These practices are generally more efficient at reducing PP than DP loss. It is also possible to modify P and N loss by *cutting* the link between source and transport pathway. Thus, incorporating manure into the soil profile by either tillage or subsurface placement reduces the potential for P and N loss in surface runoff (Sharpley et al., 1998).

All of the above approaches to control P export only work where subsurface pathways of P loss are unimportant. Phosphorus controls are effective in surface runoff generating areas but ineffective in recharge areas. The question remains as to whether they can be detrimental in such areas. Where P enrichment of surface soils has occurred due to, for example, long-term manure amendments, such control measures, by encouraging the infiltration of surface runoff, may transfer P loss from surface to subsurface delivery (Heathwaite, 1997). Downprofile translocation of potentially mobile P from P-rich soils may be significant where macropores or artificial drains exist to transport potentially mobile P (Heathwaite et al., 1999; van Riemsdijk et al., 1987). Here, the pattern of watershed land vulnerable to P loss may resemble that of N rather than P because transport control factors are less spatially delineated, as both surface and subsurface pathways may contribute P. Where it can be demonstrated that P loss in subsurface pathways is important at the watershed scale it will be necessary to modify the current P index to account for this pathway—probably by integrating some of the parameters also important for nitrate loss. However, further empirical research is needed to determine the appropriate coefficients for inclusion in a modified P index before both surface and subsurface pathways can be accommodated.

CONCLUSIONS

To date, separate strategies for P and N management have been developed and implemented at farm or watershed scales. Because of differing biology, chemistry, and flow pathways of P and N in soil, these narrowly targeted strategies may lead to conflicting or suboptimal advice. In humid climates the prevention of P and N loss from agricultural watersheds needs to shift focus to defining, targeting, and remediating source areas of P that combine high soil P levels with high erosion and surface runoff potentials, and source areas of N which coincide with soils of high permeability. Thus, differing management objectives may be appropriate for different areas of a watershed.

Essentially, both the modified P index and N index provide a categorization of the edge-of-field risk of P and N loss. Thus, on a field-by-field basis for the whole watershed we have some assessment of land use export coefficients for P and N in terms of the likelihood of nutrient mobilization. While we report research linking the spatial variation in watershed vulnerability to P loss with the variation in P concentrations in storm streamflow, the relationship between edge-of-field predictions of P and N loss and in-stream water quality remains underresearched (Heathwaite and Sharpley, 1998). Linking watershed nutrient export with stream water quality is essential to assess the impact of land management controls on receiving waters.

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