with soil on aquatic life. The vulnerability of water sources to receiving P also must be evaluated if actual impact of P movement is to be determined.

REFERENCES


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Phosphorus Movement in the Landscape

Phosphorus movement in runoff often promotes algal growth in lakes. Thus, agricultural soils and management practices that enhance the potential for P movement must be identified. The main factors controlling P movement are transport (runoff and erosion potential) and source factors (surface soil P and method, rate, and timing of fertilizer and animal manure applications). Implementation of management that minimizes runoff and erosion will reduce P transport in runoff, although total algal availability can increase. The continued application of P has increased surface soil test P contents in excess of levels sufficient for optimum crop yields. Although increases in soil P have been related to P enrichment of runoff in plot and watershed studies, information for given management systems still is needed to reliably quantify critical soil P levels above which excessive P enrichment of runoff will occur. Clearly, P applications must be carefully managed, in addition to minimizing transport potential, to efficiently reduce P movement in landscapes. This may be achieved with regular soil testing, P incorporation, application during times of low runoff probability, and irrigation management.

The movement of P in runoff from agricultural land to surface waters can accelerate their eutrophication (Levine and Schindler, 1989; Kroagstad and Lovstad, 1989). Little attention has been given to management strategies to minimize nonpoint movement of P in the landscape, due to the easier identification and control of point source inputs of P to surface waters and a lack of direct human health risks associated with eutrophication. As a result, nonpoint sources now account for a larger share of the nation’s water quality problems than a decade ago (Schultz et al., 1992; Crowder and Young, 1988).

Passage of the Clean Water Act 319 in 1987, highlighted a need and established funds to evaluate remedial strategies to minimize nonpoint source impacts of agricultural management. More studies are reporting that soil P exceeds levels required for optimum crop yields in areas of intensive agricultural and livestock production (Alley, 1991; McCollum, 1991; Pierzynski et al., 1990; Sims, 1992). Thus, a portion of the 319 funds must be used to develop economically viable management systems that minimize P movement in the landscape.

Strategies to remediate water quality problems associated with P movement in the landscape will be most efficient if sensitive or source areas within a watershed are identified, rather than implementing general strategies over a broad area. Long-term field studies that reliably evaluate P movement are costly, lengthy, and labor intensive. Thus, simulation and landform assessment tools must be developed to more rapidly identify management systems sensitive to P movement. There are many models available which simulate soil P cycling and transport in runoff. A major limitation to their use, however, is often the lack of input data to run them, because many models require detailed information on soil physical, chemical, and biological properties, as well as crop and tillage operations. Some of these limitations may be overcome by development of soil data bases. In addition, linkage of soil productivity and water quality models may be necessary to evaluate the long-term effects of agricultural management on water quality. However, a lack of adequate field data limits rigorous testing of a model’s ability to simulate a lake’s response to changes in agricultural management and weather conditions.

Abbreviations: DP, dissolved P; PP, particulate P; STP, soil test P.

Clearly, the use of many models by field personnel, such as farm advisors, extension agents, and consultants, will be restricted by data and computer requirements. Thus, an indexing system is needed to identify agricultural soils and management practices that might affect the biological productivity of receiving water bodies (Lemunyon and Gilbert, 1993).

The main factors influencing P movement can be divided into transport and P source factors (Fig. 1). Transport factors include the mechanisms by which P moves within a landscape. These are rainfall- and irrigation-induced erosion and runoff (Fig. 2). Factors which influence the source and amount of P available to be transported are soil P content and rate and method of P applied in either mineral fertilizer or organic forms (Fig. 3).

Phosphorus movement in runoff occurs as particulate P (PP) and dissolved P (DP). In general, PP is the major portion (75 to 90%) of P transported in runoff from cultivated land (Schuman et al., 1973; Sharpley et al., 1987). In terms of their impact on eutrophication, bioavailable PP represents a variable (10 to 90% of PP) but long-term source of P for algal uptake (DePinto et al., 1981; Dorich et al., 1985; Sharpley et al., 1992). Dissolved P is the most part immediately available for algal uptake (Peters, 1981; Walton and Lee, 1972). Together, bioavailable PP and DP movement in runoff represents the bioavailable P content of runoff.

In the past, P management strategies have been based mainly on total P loss. Several studies, however, have shown little decrease in lake productivity with reduced total P inputs and have attributed this to an increased bioavailability of P entering lakes (Gray and Kirkland, 1986; Young and DePinto, 1982). Consequently, the P indexing system must address the bioavailability of P moved in landscapes.

This paper discusses the role of each of the factors controlling P movement (Fig. 1) and their contribution to the development of a P indexing system (Lemunyon and Gilbert, 1993). Management strategies to minimize bioavailable P movement for each factor are presented.

TRANSPORT FACTORS

The factors by which P in both particulate and dissolved forms moves within the landscape are conceptualized in Fig. 2. As runoff enters a stream channel and, ultimately, a water body, there is generally a progressive dilution of P load through water dilution and sediment deposition. Phosphorus may become more bioavailable, however, by sorption-desorption processes and preferential transport of clay-sized material as it moves through the landscape.

In both the P indexing system (Lemunyon and Gilbert, 1993; Fig. 1) and present paper, the discussion and interpretation of P transport factors is simplified assuming erosion to control PP movement and runoff DP movement. These simplifications are made recognizing that eroding soil material is transported by runoff. In addition, factors affecting P movement in landscapes will...
be similar if erosion and runoff is induced by either rainfall or irrigation water.

Erosion

As P is sorbed by soil material, erosion determines PP movement in landscapes (Burwell et al., 1977; Garbrecht and Sharpley, 1992; Schuman et al., 1973). Sources of PP in streams include eroding surface soil, plant material, stream banks, and channel beds (Fig. 2). Thus, erosion control is of prime importance to minimizing P movement in landscapes. In landscapes with a permanent vegetative cover, such as forest or pasture, the primary source of sediment is from stream bank erosion. This sediment will have characteristics similar to the subsoils of parent material of the area, which are often of low P content.

During detachment and movement of sediment in runoff, the finer-sized fractions of source material are preferentially eroded. Thus, the P content and reactivity of eroded particulate material is usually greater than source soil. For example, the enrichment of soil test P (STP—Bray 1) and total P content of sediment in runoff from several soils under simulated rainfall ranged from 1.2 to 6.0 and 1.2 to 2.5, respectively (Sharpley, 1985b). The enrichment of P increased as erosion decreased and the relative movement of fine-particles (< 2 μm) of greater P content than coarser ones (> 5 μm) increased.

Thus, PP movement in landscapes is a complex function of rainfall, irrigation application, runoff, and soil management factors affecting erosion. The effect of erosion on PP movement is illustrated by a 15-yr study of runoff from several grassed and cropped watersheds in the Southern Plains (Sharpley et al., 1991b; Smith et al., 1991). As erosion from native grass and no-till and conventional till wheat (Triticum aestivum L.) at El Reno, OK, increased, PP was a greater portion of P transported in runoff, although amounts transported varied (0.04 to 4.5 ton/acre/yr) with management and associated fertilizer P application (Fig. 4). Accompanying the increase in PP movement is a relative decrease in DP movement (Fig. 4).

Several studies have shown that suspended sediments can rapidly sorb DP in runoff and stream flow and concluded that erosion may determine DP concentration (Klotz, 1988; Sharpley et al., 1981b; Taylor and Kunishi, 1971). Transformations between DP and PP, accentuated by the selective transport of fine material which has a greater capacity to sorb P, will thus be important in determining the bioavailability of P transported. These transformations highlight the need for the P indexing system to consider not only the total amounts of P moved as a function of agricultural management but also the bioavailability of P moved. This will lead to the development of more effective and flexible strategies to minimize the impact of P movement in landscapes on the biological productivity of receiving water bodies.

Runoff

The first step in the movement of DP in runoff is the desorption, dissolution, and extraction of P from soil and plant material (Fig. 2). These processes occur as rainfall or irrigation water interacts with a thin layer of surface soil (0.04 to 0.12 in.) before leaving the field as runoff (Sharpley, 1985a). The remaining runoff percolates through the soil profile where sorption by P-deficient subsurfaces results in low DP concentrations in subsurface flow (Table 1). Exceptions may occur in organic, permeable coarse-textured, and reduced waterlogged soils (Duxbury and Peverly, 1978; Miller, 1979; Ozanne et al., 1961; Ponnampерuma, 1972) with low P-sorption capacities.

The accelerated eutrophication of surface waters by P, is mostly associated with inputs from surface rather than subsurface flow. Thus, the P indexing system considers P movement in surface runoff only. In the few cases where P movement in subsurface runoff may be a concern, a simple N leaching index developed by Kissel et al. (1982), may be appropriate. The leaching index uses available soil survey and analytical data and is based on the texture and permeability of soil profile horizons.

The removal of P from plant and residue material by rainfall and runoff may account for differences between watersheds and seasonal fluctuations in P movement.
Table 1. Effect of fertilizer P application on the loss of P in surface and subsurface runoff.

<table>
<thead>
<tr>
<th>Land use</th>
<th>P applied</th>
<th>Concentration</th>
<th>Amount</th>
<th>Fertilizer loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Soluble</td>
<td>Partic.</td>
<td>Soluble</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lb/acre/yr</td>
<td>ppm</td>
<td>lb/acre/yr</td>
</tr>
<tr>
<td>Surface runoff</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass</td>
<td>0</td>
<td>0.18</td>
<td>0.24</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.96</td>
<td>0.96</td>
<td>2.50</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>0.03</td>
<td>0.14</td>
<td>0.04</td>
</tr>
<tr>
<td>No till corn for grain</td>
<td>0</td>
<td>0.23</td>
<td>0.46</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.57</td>
<td>0.51</td>
<td>1.11</td>
</tr>
<tr>
<td>No till corn for silage</td>
<td>0</td>
<td>0.23</td>
<td>0.43</td>
<td>0.63</td>
</tr>
<tr>
<td>Conventional corn</td>
<td>13</td>
<td>0.07</td>
<td>3.57</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>0.11</td>
<td>9.71</td>
<td>0.18</td>
</tr>
<tr>
<td>Contour corn</td>
<td>36</td>
<td>0.19</td>
<td>7.11</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.25</td>
<td>2.27</td>
<td>0.13</td>
</tr>
<tr>
<td>Wheat-summer fallow</td>
<td>0</td>
<td>0.30</td>
<td>1.80</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>3.70</td>
<td>7.40</td>
<td>1.07</td>
</tr>
<tr>
<td>Subsurface runoff</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa (tile drainage)</td>
<td>0</td>
<td>0.18</td>
<td>--</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>0.21</td>
<td>--</td>
<td>0.17</td>
</tr>
<tr>
<td>Continuous corn (tile drainage)</td>
<td>0</td>
<td>0.02</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>Bluegrass sod</td>
<td>0</td>
<td>0.23</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>Oats</td>
<td>0</td>
<td>0.02</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0</td>
<td>0.02</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Grass</td>
<td>0</td>
<td>0.06</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.19</td>
<td>0.16</td>
<td>0.39</td>
</tr>
</tbody>
</table>

† Percentage decrease in P loss from fertilized compared with check treatment.

(Gburek and Heald, 1974; Wendt and Corey, 1980). A more complete understanding and consideration of all processes controlling DP movement will increase the sensitivity of the P indexing system to landscape management.

SOIL FACTORS

Soil Test P Levels

Decades of P fertilization at rates exceeding those of crop removal have resulted in widespread increases in STP levels. For example, an average of 48 ppm of STP (Bray-1) was present in all soils tested in Wisconsin, with an average of 72 ppm of STP for coarse textured soils, reflecting their extensive use in vegetable production (Combs and Burlington, 1992). Generally, no economic response in crop yield is attained from further addition of P fertilizer when STP (Bray-1) exceeds 50 ppm.

Crop yield response to STP is shown in Fig. 5, which conceptualizes the process of making fertilizer P recommendations based on STP. As shown earlier, continual long-term P applications have raised STP above levels required for optimum crop yields. Once STP levels be-

Fig. 5. Relationship between crop yield, soil test P, and the potential for environmental problems due to excessive soil test P.

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come excessive, the potential for P movement, if runoff and erosion occur, is greater than any agronomic benefits of further P applications. Thus, the P indexing system accounts for the effect of STP on environmental and agronomic impacts.

After high levels of STP have been attained, considerable time is required for significant depletion. For example, McCollum (1991) estimates that without further P addition, 8 to 10 yr of cropping corn (Zea mays L.) or soybean [Glycine max (L.) Merr.] will be required to bring a Portsmouth (fine-loamy over sandy or sandy skeletal, mixed, thermic Typic Umbrault) sand from 54 ppm STP (Mehlich-III extraction) to 20 ppm. Pierzynski et al. (1990) examined several midwestern soils and found 218 and 246 ppm STP (Bray-1) in a Wisconsin Plainfield sand (fine, illitic, mesic Aeric Ochraqualf) and an Illinois Blount silt loam (mixed, mesic Typic Udipsamment), respectively, and attributed these levels to addition of commercial fertilizer.

While STP levels of soil profiles (0–6 in.) have been increasing over time due to commercial fertilizer application, recent changes in farming practices, such as acceptance of conservation tillage systems, have also dramatically influenced the level of STP in the runoff sensitive portion of the soil surface (1 in.). In the case of conservation tillage, increases in STP of the surface horizon can be attributed to surface fertilizer application without soil profile inversion. The long-term tillage study of Griffith et al. (1977) demonstrates the typical stratification of STP level under no-till conditions. Within a few years, the surface layer of no-till was six times higher than initial STP levels. Levels of STP also are elevated by long-term land application of wastes. Application of dairy manure has contributed to 200 ppm STP (Bray-1) levels in Wisconsin (Motschall and Daniel, 1982), and Pierzynski et al. (1990) showed levels of 613 ppm of STP (Bray-1) in Illinois as a result of sludge additions. Sharp et al. (1991c) examined several Oklahoma soils receiving long-term application of poultry litter and found STP (Bray-1) levels of up to 279 ppm.

Several agricultural practices can lead directly to elevated DP levels in runoff. However, a potentially more important and difficult-to-manage source of P to surface waters is the ubiquitous contribution of DP from elevated STP levels. Accumulation of STP near the soil surface due to previous P application influences the concentration and loss of P in runoff (Oloya and Logan, 1980; Sharp et al., 1981a). In fact, a highly significant linear relationship has been demonstrated between the amount of STP in the surface soil and DP concentration of surface runoff (Hanway and Lafien, 1974; Romkens and Nelson, 1974; Sharp et al., 1978, 1981a; Oloya and Logan, 1980).

Sharp et al. (1981a), using simulated rainfall, investigated the effect of several variables on P transport in runoff. The level of STP along with runoff volume, depth of soil-runoff interaction, and soil bulk density, were shown to directly influence DP transport. Sharp et al. (1986), using watershed data, also demonstrated the effect of management on the relationship between DP concentration in the runoff and the amount of available P in the surface soil (Fig. 6).

Continued work culminated in an equation describing the kinetics of soil P desorption and predicting DP transport in runoff (Sharp and Smith, 1989):

$$P_r = \frac{(K_P E B t^\sigma W^\beta)}{V} \quad [1]$$

where $P_r$ is the average DP runoff concentration, $P$ the Bray P content of the surface soil, $E$ the depth of interaction, $B$ the soil bulk density, $t$ the duration of runoff, $W$ the runoff water/soil ratio, $V$ the total amount of runoff, and $K$, $\sigma$, and $\beta$ are constants for a given soil.

Using this equation, Sharp and Smith (1989) obtained a close agreement between predicted and measured DP concentration in runoff from long-term watershed studies. To obtain an estimate of the quality of the runoff, the model was used to predict DP concentration from fields having received long-term application of swine (Sus scrofa domesticus) and poultry manure (Sharp et al., 1991c). Runoff DP concentrations were predicted from fields (Captina silt loam, fine-silty, siliceous, mesic Typic Fragiudult) having P levels of 5, 121, and 279 ppm, brought about by historic application of no manure/fertilizer, swine manure and poultry manure, respectively. Peak concentrations of 4.5 and 1.8 ppm DP were predicted for the runoff from fields having received poultry and swine waste, respectively. These concentrations were 33- and 14-fold greater than from the untreated area (to manure/fertilizer). According to these workers, the potential exists for accelerated eutrophication, should runoff from such fields enter lakes or streams.

### Soil Test P Measurement

At present, STP determined by various methods is being used to assess the potential for a given landscape to enrich the P content of runoff. Many studies, however, show the variability in STP estimated by different methods for a large selection of soil types (Sharp, 1991; Wolf et al., 1985). Though various methods have been developed to accurately assess plant availability of P on a regional basis, they may not be appropriate to relate...
soil P to potential enrichment of bioavailable P in runoff. Thus, there is need for a standardized method to evaluate soil P status for environmental rather than agronomic considerations.

The bioavailable P content of runoff or lake sediment can be measured by algal assay methods, which require from 7- to 100-d incubations (Lovstad and Krogstad, 1990; Miller et al., 1978). Thus, more rapid chemical extraction (Dorich et al., 1980; Hegemann et al., 1983; Sharpley et al., 1991a) and iron oxide-impregnated paper strip methods (Sharpley, 1993) have been developed to routinely estimate the bioavailable P content of a soil or runoff. The latter method, like recent resin accumulators or strips (Skogely et al., 1990; Yang et al., 1991) act as a sink for algal available P and are thus, independent of soil type. They have been shown to estimate available P equally well in both acidic and basic soils (Sharpley, 1991). Although further development and testing of these P-sink methods are needed, they may provide an environmental test for soil P bioavailability.

Phosphorus Application/Management

Loss of P in the runoff is influenced by the rate, time, and method of fertilizer application; form of fertilizer; amount and duration of rainfall or irrigation; and vegetative cover. Percentage loss of applied P transported in runoff for the studies reported in Table 1, was generally greater from conventional than from conservation tilled watersheds. Also, the amount of fertilizer P transported in runoff is generally less than 5% of that applied.

Early workers (Romkens and Nelson, 1974; Baker and Laflen, 1982) established a clear relationship between P application rate and method and amount of P transported in runoff. In a classic study combining field and lab investigations, Romkens and Nelson (1974) demonstrated a linear relationship between the amount of P added as superphosphate fertilizer and P loss in runoff. Using simulated rainfall, Baker and Laflen (1982) later confirmed the work of Romkens and Nelson (1974) and further demonstrated the effect of fertilizer placement on P transported in runoff. Runoff DP concentration averaged 100 times higher from areas receiving broadcast fertilizer than from areas where comparable rates of fertilizer P were point-injected below the soil surface. Using manure as the source of P, Westerman et al. (1983) demonstrated a direct relationship between the quality of runoff water and application rate of poultry manure. Mueller et al. (1984), in a field study using dairy manure and simulated rainfall, showed that P loss was five times higher from areas receiving broadcast treatments of manure than from incorporated manure.

Timing of land application of P and the occurrence of intense runoff events is an overlooked factor in management programs to limit P in runoff. Generally, the bulk of P transported in runoff occurs in one or two intense events during a year. If the occurrence of intense storms is in concert with recent P application, then percentage loss of applied P is expected to be higher than if applications were made during times of the year when runoff probabilities were lower (Edwards et al., 1992). Burwell et al. (1975), using watershed studies, demonstrated that P loss was greatest during the planting season; a time consistent with the most intense rains, P application, and minimum crop cover.

Time between application of P and the first runoff event is also important, especially in situations involving manure. An evaluation of the effect of interval between P application and first runoff-producing storm was performed by Westerman and Overcash (1980). In this study, both swine and poultry manures were applied to plots and simulated rainfall applied at intervals ranging from 1 to 3 d following manure application. Total P concentrations in the runoff were reduced 90% by delaying the first runoff event 3 d, according to these investigators, due to increased time for P sorption.

MINIMIZING P MOVEMENT

Phosphorus movement in landscapes can be reduced by careful mineral and organic fertilizer management and erosion and runoff control. Overall, the cost and difficulty of control measures increases as the distance between P source and treatment increases. Thus, identification and subsequent control of potential P sources of movement in a landscape must be emphasized. One of the aims of the P indexing system is to identify sites that may be vulnerable to P movement.

Fertilizer Management

Where possible, subsurface placement of P away from the zone of removal in runoff will reduce the potential for P movement. It also may be necessary to periodically plow no till soils to redistribute surface P accumulations throughout the root zone. Both practices may indirectly reduce the transfer of P to surface runoff by increasing crop uptake of P and thus yield, which affords greater vegetative protection of surface soil, reducing erosion.

Efficient use of organic P sources presents a greater challenge to farmers. In high density animal producing areas, the amount of nutrients in manure often exceeds crop requirements and area of land available for application. The cost of transporting low-density manure exceeds its nutrient value within short distances, however. Historically, strategies for land application of animal manures have been based on meeting the N needs of the crop being produced. Following this approach can often lead to an excessive accumulation of soil P, due to the lower ratio of N:P added in manure than taken up by crops. Beef and dairy cattle (Bos taurus L.), pork, sheep (Ovis aries), and swine manure has an average N:P ratio of 3 (Gilbertson et al., 1979), while the N:P requirement of major grain and hay crops is 8 (Fertilizer Institute, 1982). Consequently, management of these P resources should include careful timing and attention to rate of application.

Manure application rates based on N can be justified for groundwater protection, but their relationship to surface water quality is questionable. Benchmark research is needed to design programs that limit P in the runoff and N transport to the groundwater. Generally, such an
approach would automatically limit N application, reduce DP runoff losses, and prevent the long-term build up of STP. Thus, on soils vulnerable to runoff and having a STP level of medium or above, manure applications should be made on a P basis. Use of the P indexing system will aid these management decisions.

Erosion and Runoff Control

Phosphorus movement via erosion and runoff may be reduced by increasing cover through conservation tillage (Fig. 7). Dissolved P concentration of runoff from no till practices were greater, however, than from conventional practices. Reducing tillage operations also increased the portion of total P that was bioavailable in both dissolved and particulate P forms (Fig. 7). In addition, management of irrigation water added, particularly in furrow irrigation, will reduce P loss by minimizing induced runoff and erosion.

Filter strips or zones can effectively reduce erosion and P movement, as shown by Dillaha et al. (1989) for orchardgrass (Dactylis glomerata L.) strips in Virginia (Fig. 8). Although the 30 ft strip reduced DP movement 44% on the 11% slope, DP increased 78% with the 15 ft strip. On the 5 and 16% slopes, strip length did not affect DP loss (Fig. 8). Dillaha et al. (1989) attributed the DP increase to lower removal efficiencies for soluble nutrients and release of P previously trapped in the filters.

Additional measures to reduce the potential for P movement by erosion and runoff include terracing, contour tillage, cover crops, tile drainage, and impoundments or small reservoirs. Most of these practices, however, are more efficient at reducing PP than DP movement in runoff. For example, DP concentrations were greater in runoff from conservation than conventional till (Fig. 7) and buffer strips had no consistent effect on DP (Fig. 8). In all cases, DP concentrations exceeded critical values associated with accelerated eutrophication (0.01 to 0.05 ppm) (Sawyer, 1947; USEPA, 1976). Consequently, implementation of erosion and runoff control measures alone may not reduce the potential for P-associated eutrophication as well as may be expected from inspection of total loads only. Clearly, effective control strategies must address both transport and source factors outlined in the P indexing system to minimize bioavailable P movement in landscapes.

CONCLUSIONS

Assessing the relative impact of agricultural management on P movement in landscapes is important from both agronomic and environmental aspects. Agronomically, P movement from an agricultural field represents a loss of valuable plant nutrients from a farming system. Generally, this loss of P is not of economic importance to a farmer. However, it often leads to the deterioration of water quality from accelerated eutrophication, that can have significant offsite economic impacts. By the time these impacts are manifest, remedial strategies are often difficult and expensive for the landowner to implement; they cross political regional boundaries; and it can be several years before an improvement in water quality occurs. Thus, a rapid, simple system is needed to assess the effect of agricultural management on the vulnerability for P movement from landscapes. The P indexing system has been developed as a field tool to fill this need.

In developing the P indexing system (Lemunyon and Gilbert, 1993), the transport (erosion and runoff) and source factors (STP and P applications), have been incorporated as they relate to P movement. The P indexing system will identify sources of P movement within a watershed or basin area. This will be of prime importance in targeting effective remedial strategies to minimize P movement.

The index also will allow an evaluation of the relative importance of P transport factors and whether P move-
ment occurs primarily in dissolved or particulate forms. For example, a field under conservation tillage may be identified as being vulnerable to P movement in runoff as a result of STP accumulation at the surface. In this scenario, DP will be the major form of P transported. Thus, remedial measures should prioritize P management rather than erosion control. Clearly, the P indexing system will allow more flexible remedial options to be targeted and adopted. Hopefully, this will lead to the development of sustainable agricultural management systems that are both agronomically and environmentally sound.

REFERENCES

Fig. 8. Phosphorus movement in runoff from a tilled, fallow Groseclose silt loam (clayey, mixed, mesic Typic Hapludult), as a function of soil slope and length of orchardgrass buffer strip (data adapted from Dillaha et al., 1989).
