The Selective Removal of Phosphorus from Soil: Is Event Size Important?

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ABSTRACT

Data from the Woburn Erosion Reference Experiment (Bedfordshire, UK) were used to test the hypothesis that losses of phosphorus (P) in small erosion events are as great as those in infrequent large events, and to examine the effect of storm characteristics on the selective enrichment of P in eroded sediment. For almost every plot event in the period 1988 to 1994, the clay-sized fraction of the sediment was enriched compared with the soil of the plots. There was more variation in clay enrichment for smaller erosion events than for larger ones. The clay and P contents of the sediment were strongly correlated ($p < 0.01$), and there was a wider range of P concentrations in the sediment derived from small events than in that from large events. However, individual events resulting in small soil losses (<100 kg) did not account for greater P losses than larger events (>100 kg). The greater frequency of smaller events, combined with the likelihood of higher P concentrations in the sediment, therefore accounted for a greater proportion of the P lost over the 6-yr period than the infrequent large events. Phosphorus concentrations generally increased with increasing peak discharge and decreased with increasing event duration. For the same return period, P losses were generally greater from plots cultivated up and down the slope than from those cultivated across the slope. Overall, our results suggest that small erosion events should be controlled to prevent P contamination of surface waters and that the most effective means of doing this are by the introduction of minimal tillage techniques and across-slope cultivations.

As point-source discharges of P become increasingly controlled, greater attention is being given to the transport of P to surface water bodies from diffuse sources, which are often related to agriculture. Phosphorus occurs both naturally within the soil and as additions to it in the form of inorganic and organic fertilizers and animal wastes. The effects of such additions on P losses from croplands are increasingly well documented (Tunney et al., 1997; Edwards and Withers, 1998; Haygarth et al., 1998; Carpenter et al., 1998; Pote et al., 1999). Haygarth et al. (1998) estimated that annual P inputs for a dairy farm in the west of England are 44 kg ha^{-1} yr^{-1}, while outputs are approximately 26 kg ha^{-1} yr^{-1}. The 18 kg ha^{-1} yr^{-1} surplus is similar to those calculated for farms elsewhere in Europe (Brouwer et al., 1995).

Unlike nitrate, P is relatively insoluble and adheres strongly to soil minerals and organic matter. Most of the P in soils, other than peat, is held in mineral particles and is termed nonexchangeable by Wild (1988). It is relatively unavailable, but can be released to be held on soil mineral surfaces where it buffers the soil solution. Although the release of nonexchangeable P is slow, the large quantities in soil minerals can maintain the concentrations of exchangeable P on the soil surface for a considerable time. For example, McIsaac et al. (1991) suggests that it may take 16 to 18 yr of production of unfertilized maize (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] to reduce the soil P availability of a Typic Umbraquult from 100 mg kg^{-1} to the agronomic limit of 20 mg kg^{-1}.

As much of the soil P is associated with particle surfaces, soil erosion is likely to be an important mechanism for transporting P from agricultural fields to the aquatic environment. For example, Catt et al. (1998) showed that losses of P from experimental plots in the UK occur mainly in particulate forms and are consequently greater in surface runoff than drain flow. On the sandy soil of the Woburn Erosion Reference Experiment, losses of total P associated with sediment were 0.8 to 18.7 kg ha^{-1} yr^{-1} for a 6-yr arable rotation.

The amounts of P transported in overland flow can be concentrated by the selective nature of water erosion, as P is associated primarily with the finer fractions of the soil (Syers and Walker, 1969), which often are transported preferentially. Theoretically, selection of fine particles can occur during two stages: detachment and transport. The finer fractions of the soil, once in suspension, travel further, so there is enrichment of finer materials as the distance of travel increases.

Enrichment of nutrients in surface runoff has often been reported (Frere et al., 1980; Flanegan and Foster, 1989; Smith et al., 1993; Catt et al., 1994). Enrichment ratios are often given, but these are of only limited use since they apply to particular conditions of erosion, and the composition of suspended sediments varies enormously in time and space. This variation is caused by a number of factors including texture, aggregate characteristics, vegetation cover, gradient, and slope length (Young, 1980). In addition, event characteristics are also important. The distance travelled by overland flow depends upon the storm characteristics, the hydraulic properties of the slope, and the slope length (Smith and Quinton, 2000). As both the storm and hydraulic characteristics vary between storms, the selectivity of redeposited material must also vary.

There is some disagreement in the literature considering the relative importance of different erosion processes as agents for selective detachment. Poesen and Savat (1980), Poesen (1985), and Parsons et al. (1991) suggest that detachment by raindrops is not selective. However, Torri and Sfalanga (1986) reported selective

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Table 1. Selected soil properties for the Woburn Erosion Reference Experiment.

Soil property	Value
Percent coarse sand (>600 μm)	1.7
Percent medium sand (212–600 μm)	44.9
Percent fine sand (63–212 μm)	36.3
Percent silt (2–63 μm)	9.7
Percent clay (<2 μm)	5.9
Bicarbonate-extractable phosphorus (mg kg^{-1})	40–60
Total phosphorus (mg kg^{-1})	808–1137

detachment of material in the 0.063- to 0.5-mm size range from clay-rich aggregates. This discrepancy may result from the researcher's choice of soil: each soil except the one studied by Torri and Sfalanga (1986) had poor aggregation or was a noncohesive sediment, perhaps making all size classes equally vulnerable to detachment.

In overland flow, selectivity appears to increase with declining energy (Palis et al., 1990). In rainfall simulation experiments on a sandy soil in the Walnut Gulch experimental area (Arizona), Parsons et al. (1991) found that sediment sampled from overland flow was finer than the original soil. They assumed that interrill flow was unable to transport the coarse fraction of the soil. They also found no difference in selectivity at different positions down the slope. Their results are corroborated by Profitt and Rose (1991), who found sheet erosion to be more selective than rill erosion. Although soil loss from sheet erosion is likely to be many times smaller than that from rill erosion, the higher concentrations of nutrients associated with finer soil material means that it should not be overlooked as a mechanism of nutrient transport (Rose and Dalal, 1988; Palis et al., 1990).

Geomorphologists and erosion scientists are often concerned with large events. In mid-Bedfordshire, Morgan et al. (1986) showed that two or three events each year are likely to be responsible for most of the annual soil loss. This is supported by work in the USA (Edwards and Owens, 1991) and Nigeria (Lal, 1976). However, as less energy is required to detach and transport smaller particles, it seems possible that smaller but more frequent events may be responsible for a disproportionately large amount of the annual P loss. In this paper, we examine data from the Woburn Erosion Reference Experiment (Catt et al., 1994) to test the hypothesis that small erosion events are as important as large erosion events in transporting P from agricultural land, and to investigate the mechanisms responsible for the selective transport of P.

Table 2. Monitoring level and treatments for the eight plots of the Woburn Erosion Reference Experiment. For monitoring, *auto* indicates hydrographs and sediment samples collected in addition to event totals, while *man* indicates that only total runoff and sediment loss were measured. U = cultivations up and down the slope, A = cultivations across the slope, M = minimal tillage with residues retained, and S = standard tillage with residues removed.

Plot	Monitoring	Cultivation direction	Tillage
1	man	U	M
2	man	A	S
3	man	A	M
4	man	U	S
5	man	A	S
6	auto	U	M
7	auto	U	S
8	auto	A	M

MATERIALS AND METHODS

Data were collected from eight erosion plots located at Woburn Experimental Farm, Bedfordshire, UK (0°33′5″ W, 52°0′45″ N). Soils at the site range in texture from loamy sand to sandy loam and correspond to the Cottenham and Lowlands series defined by Clayden and Hollis (1984) and classified as Lamellic Ustipsamment and Udic Haplustept, respectively (Soil Survey Staff, 1999). Mean soil characteristics determined from analyses of topsoil samples are given in Table 1. Slopes on the site vary between 7 and 13%. Details of the treatments and cropping patterns are given in Tables 2 and 3. The experiment was established after harvest in 1988 and the first crop of potato (*Solanum tuberosum* L.) was planted in the following spring. This crop was followed by two winter cereals [wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.)], then sugar beet (*Beta vulgaris* L.) and two more years of winter cereals, a rotation common in the area. Two main treatments were used in the experiment: cultivation direction (either up and down or across slope) and residue management (residues retained and partially incorporated by shallow tine cultivation or removed before moldboard plowing). The plots were arranged in two blocks, within which each combination of the two treatments is represented. Each plot measured approximately 25 by 35 m and was isolated from the rest of the slope by a low earth bank. Soil and water flowing off each plot were channelled to a collecting trough and through a pipe to two 2000-L tanks, where they were stored until sampling. The

Table 3. Crop rotation, phosphorus fertilizer applications, rainfall, number of rain days, and numbers of runoff events for the eight plots of the Woburn Erosion Reference Experiment (1988–1994).

Year	Crop	Phosphorus fertilizer applications	Rainfall	Rain days	Numbers of erosion events (range)
		kg ha^{-1}	mm		
1989	potato	102	153	47	0–1
1989	fallow	0	45.1	12	0–1
1989–1990	winter wheat	0	459.8	105	10–13
1990	fallow	0	33.6	12	0
1990–1991	winter barley	0	512.2	152	0–2
1991–1992	fallow	0	335.1	96	0–1
1992	sugar beet	118	597.2	118	2–10
1992	fallow	0	172.4	42	6–9
1992–1993	winter wheat	0	350.4	91	0–2
1993	fallow	0	201.3	36	0
1993–1994	winter barley	0	492.6	152	0–7

amount of runoff and soil loss from each plot was determined as soon after each runoff event as practically possible and usually within 48 h. In addition, three of the plots were instrumented with pressure transducers (Druck [Leicester, UK] PDCR 830) linked to a datalogger (Campbell Scientific [Logan, UT] CR10) to measure the depth of water in the tank every minute during runoff events (Table 2). This information allowed hydrographs to be constructed. Samples of the runoff and sediment were taken for physical and chemical analysis. Particle size distribution was determined by the pipette method (Avery and Bascomb, 1974). A representative subsample of the sediment was air-dried and ground in an agate mill before being digested in aqua regia and analyzed for total P using an inductively coupled plasma arc spectrophotometer (ICP). Runoff samples were also analyzed using the ICP after microfiltration, but the results are not considered in this paper as the amounts of P transported in this form are much less (Catt et al., 1994) and do not show selectivity relationships. The data used in this paper relate to the period 1988 to 1994, during which 47 erosion events occurred on one or more plots at the site.

RESULTS

Selectivity of Erosion and Deposition

Figure 1 shows that for almost every plot event the clay-sized fraction of the sediment was enriched compared with the soil of the plots. It also shows more variation in clay enrichment for smaller erosion events than for larger ones, although only a small number of larger events occurred during the measurement period. Mean clay contents in events with a soil loss of <100 kg were 35.4%, which is significantly greater ($p < 0.01$) than the mean of 8.54% for events with a soil loss >100 kg. The relationship between clay and P content of the sediment is strong (Fig. 2). Consequently, the relationship between P concentration in the sediment and event magnitude (Fig. 3) exhibits a similar pattern to Fig. 1, showing a wider range of P concentrations in the sediment derived from smaller events than in that from larger events.

Having established that P was selectively transported as fine particulate material from the plots, it is useful to examine the actual amounts moved to see whether the greater selectivity of smaller events accounted for more P loss than larger events, which had lower P concentrations. Figure 4 shows that individual plot events resulting in smaller soil losses did not generally account for more P loss than larger events. However, for events resulting in total soil losses >115 kg, P losses did not exceed a maximum of 215 g per event regardless of event magnitude. Figure 4 also suggests that there may be two or more distinct groups within the data. These could result from different plots, blocks, crops, crop covers, or events, but no single explanation could be found.

Figures 1, 3, and 4 all show that there were many more events of small magnitude than there were of large magnitude, so the greater frequency of smaller events, combined with the likelihood of higher P concentrations in the sediment from them, may account for a greater proportion of the P lost over the 6-yr period than the infrequent large events. For each plot the amount of P loss for each event was calculated as a percentage of the total 6-yr loss and plotted against the soil loss as a percentage of the total 6-yr soil loss. The data from Plot 7 are illustrated in Fig. 5, as this plot erodes most frequently, but all the other plots show similar relationships. Figure 5 shows that smaller events, accounting for 50% of the total soil loss, accounted for 80% of the total P lost from the plot; and that 50% of the P lost from the plot over the 6-yr period was transported in the 25% of soil lost in the smallest events.

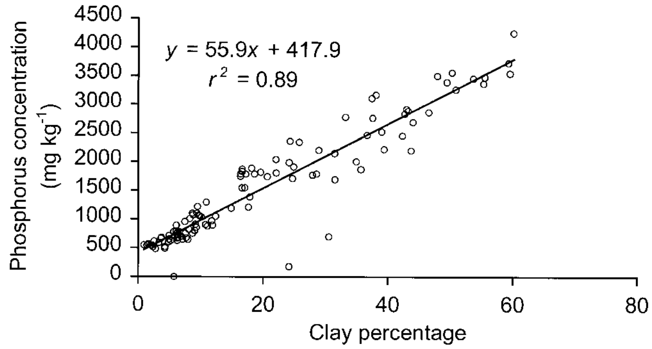

Fig. 2. Relationship between P concentration and percentage of clay-sized material in the eroded sediment from all plot events at the Woburn Erosion Reference Experiment (1988–1994).

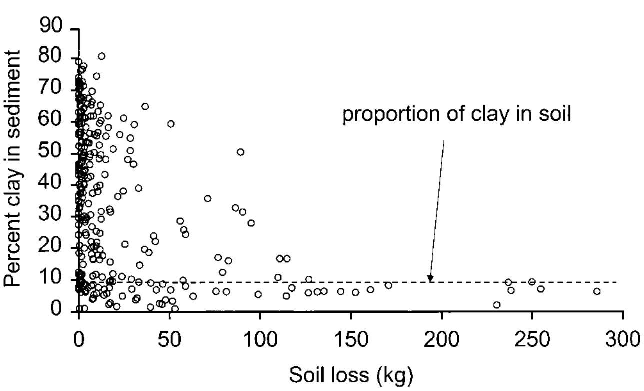

Fig. 1. The proportion of soil lost as clay (<2 μm) plotted against total soil loss for the 47 events from 1988 to 1994 at the Woburn Erosion Reference Experiment. The dotted line gives the percentage of clay in the parent soil.

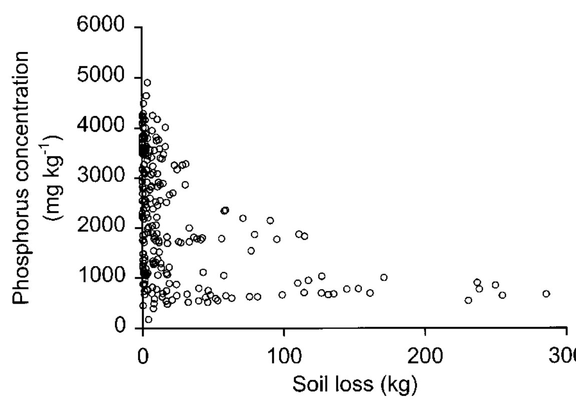

Fig. 3. The relationship between P concentration in the eroded sediment and event magnitude, represented by the total soil loss per event, for all plot events in the Woburn Erosion Reference Experiment (1988–1994).

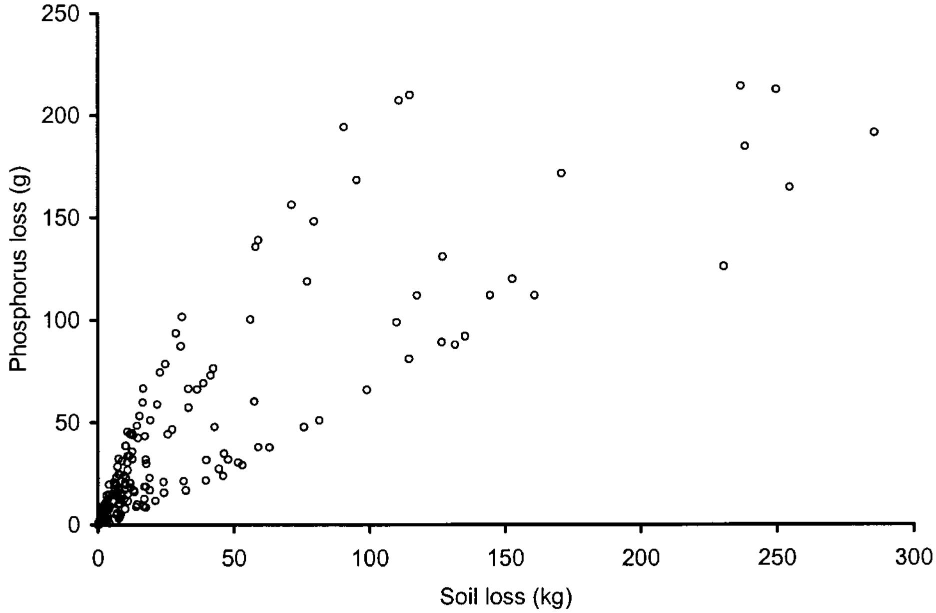

Fig. 4. Relationship between the amount of P in the eroded sediment and event magnitude, represented by the event soil loss, for all plot events in the Woburn Erosion Reference Experiment (1988–1994).

Effect of Event Characteristics

To investigate the variation in P concentrations for low-magnitude events (Fig. 3), soil losses were plotted against peak discharge (Fig. 6a) and flow duration, defined as the time from the first measurement of runoff to the time that runoff ceased (Fig. 6b), for the three plots (6, 7, and 8) with automated runoff recording (Table 2). Both peak discharge and event duration showed large variability at low soil losses, suggesting that they may be responsible for the variations in P concentration. Despite this, plots of P concentration against peak discharge (Fig. 7a) and flow duration (Fig. 7b) showed no clear relationships. However, the points in Fig. 7a,b with the highest P concentrations (enclosed) all occurred after the harvest of sugar beet in 1992, and are significantly different ($p < 0.01$) from the other points. The crop had received an application of 118 kg P ha^{-1} on 1 April of that year, and these higher concentrations can be explained by a combination of residual fertilizer from this application and fresh soil brought to the surface during harvest and then removed by autumn erosion. If the points within the circle are discounted, then P concentrations generally increase with increasing peak discharge ($r = 0.53, p < 0.01$) and decrease with increasing event duration ($r = -0.42$, $p < 0.1$).

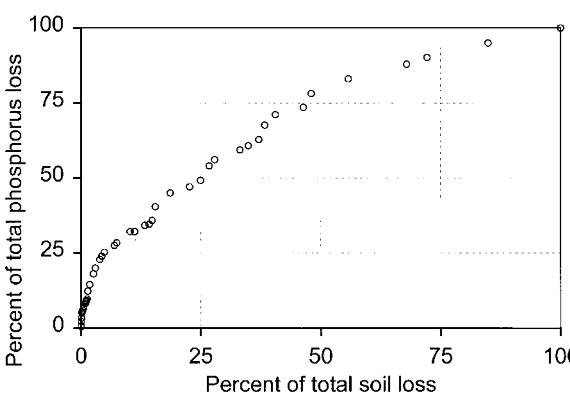

Fig. 5. Percent of total P loss for each event (1988–1994) plotted against percent of the total soil loss for Plot 7 (up and down slope, minimal tillage) of the Woburn Erosion Reference Experiment (1988–1994).

Effect of Treatments

The effects of minimal tillage, standard tillage, and cultivation direction on event P loss and total P loss in the sediment during the experimental period are presented in Fig. 8a and 8b, respectively. Both figures show that losses of P were least when across-slope cultivations were combined with minimal tillage and residue retention. However, when examined by analysis of variance, these differences were not found to be significant.

Treatment effects on total P loss for each crop and fallow period were also examined by analysis of variance (Table 4). In most periods, tillage up and down the slope produced greater P losses, though significant differences ($p < 0.05$) were found only for potato in 1989, sugar beet in 1992, and the second crop of winter wheat in 1992 and 1993.

Return Period Analysis

From the Woburn data it is also possible to calculate typical return periods for the different magnitudes of P loss. Each event is assumed to be independent. The event P loss is then ranked and the return period (T_p) of an event with a magnitude greater than or equal to x is calculated using Eq. [1]:

$$T_p = N/(n \geq x) \quad [1]$$

where N is the number of years of the record and $n \geq x$ is the number of events with a magnitude equal or greater than x. Generally speaking, for the same return

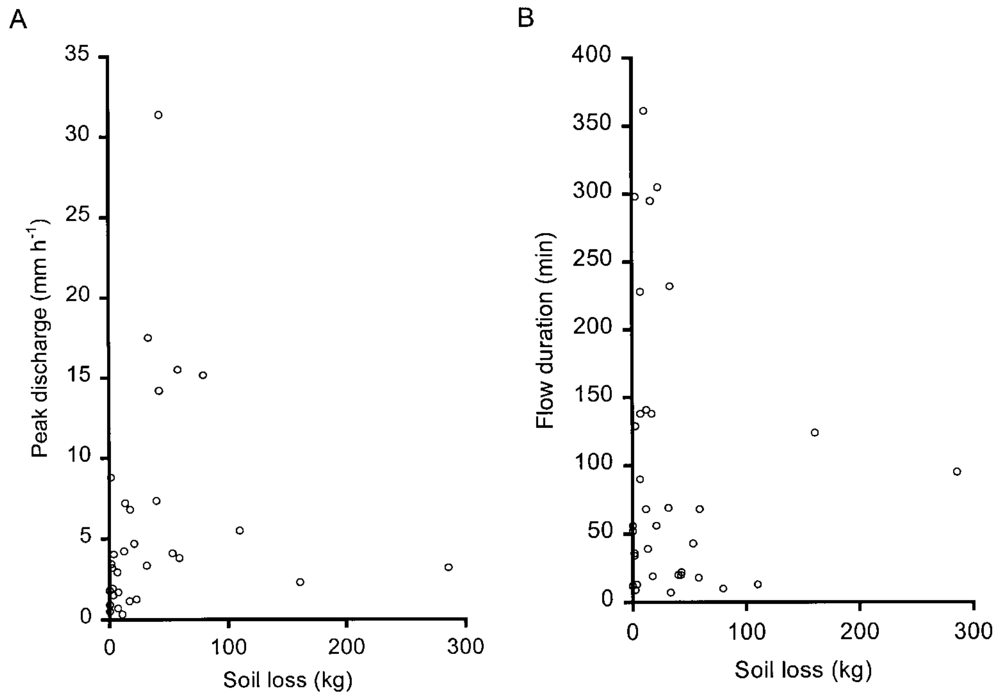

Fig. 6. Relationship between event soil loss and (*A*) peak discharge and (*B*) flow duration for plot events with automatic discharge records in the Woburn Erosion Reference Experiment.

period, P losses were highest from those plots cultivated up and down the slope (Fig. 9). However, the only significant difference ($p < 0.05$) was that between the mean 6-yr return period losses from the two across-slope minimal-tillage plots and that from the two up and down–slope minimal-tillage plots. The frequency–magnitude relationship can also be illustrated graphically. Figure 10 shows this relationship for two plots with contrasting treatments: Plot 7, an up and down–slope plot with standard cultivations, and Plot 3, an across-slope plot with minimal tillage. As expected, it shows that higher-magnitude events have longer return periods. On Plot

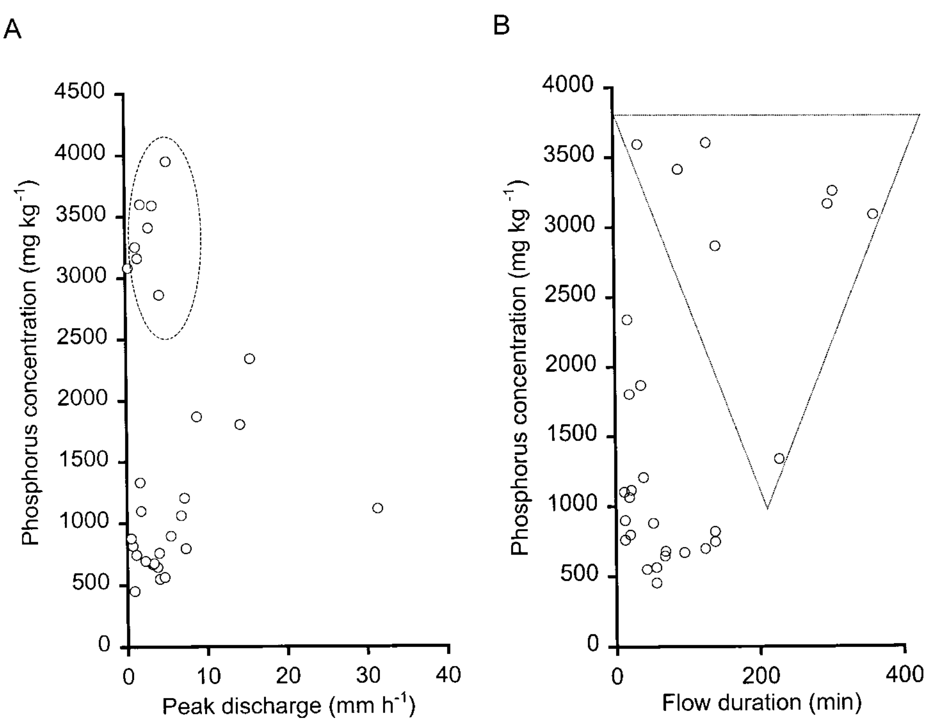

Fig. 7. Relationship between P concentrations and (*A*) peak discharge and (*B*) flow duration for plot events with automatic discharge records at the Woburn Erosion Reference Experiment. The points inside the dotted line represent events after the harvest of sugar beet in autumn of 1992.

7, event losses of 100 g of P are expected to occur with a frequency of approximately one per year, whereas on Plot 3 events with a return period of 1 yr cause losses of no more than 5 g P.

DISCUSSION

Management

The result that low-magnitude events with a high frequency account for much of the P loss from the Woburn plots has implications for protecting watercourses from enrichment with P. Within the UK, soil erosion is viewed as only of local importance, and as a threat to the productivity of arable agriculture this view is perhaps correct. However, the amount of erosion required to cause environmental damage is much less than that needed to affect arable agriculture. English Nature (1997) propose a maximum acceptable limit of orthophosphate of 0.1 mg L^{-1} for clay catchments and alluvial lowland rivers and 0.06 mg L^{-1} for rivers on chalk, hard sandstone, and limestone. Mean total P concentrations in erosion from the Woburn plots, at 25 mg L^{-1}, are more than two orders of magnitude greater than the English Nature limits. This suggests that if the runoff were to connect with a watercourse, the potential for pollution would be high. We therefore propose that erosion control measures should be targeted at areas where events are likely to connect with watercourses, even if they are of small magnitude. In the UK, small events occur on most soil types under arable crops grown on slopes. Our results suggest that the most effective way of achieving control under these conditions is by orientating cultivations and crop rows on the contour and practicing minimal tillage.

Process

Our work supports the conclusions of Young (1980) and others that preferential loss of fine P-enriched soil particles is influenced by a number of factors. Figure 3 shows that although there is a general decline in selectivity of P with event magnitude, there is a great deal of scatter, especially in smaller events. After careful analysis of our data we cannot wholly explain this. The decline in P concentrations with event duration (Fig. 7b) supports the suggestion of Teixeira and Misra (1997)

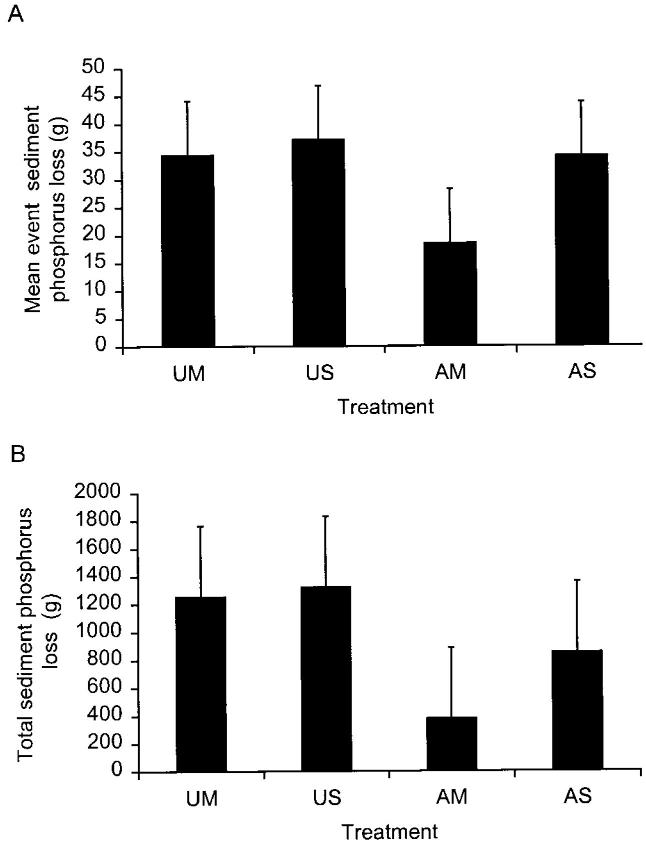

Fig. 8. Effect of treatments on (*A*) the mean event sediment P loss and (*B*) the total sediment P loss from the Woburn Erosion Reference Experiment (1988–1994). U = cultivations up and down the slope, A = cultivations across the slope, M = minimal tillage with residues retained, and S = standard tillage with residues removed. Bars indicate one standard error.

that finer sediment is preferentially transported in the first few minutes of an erosion event. This may be because the soil particles transported in the early part of an event are stripped from aggregate surfaces, which have higher concentrations of applied chemicals (Ghadiri and Rose, 1991; Wan and El Swaify, 1998).

The increase of P concentrations with peak discharge rate (Fig. 7a) is contrary to the suggestion that small erosion events are the most nutrient selective (Massey and Jackson, 1952). One possible explanation is that when finer material is initially removed preferentially

Table 4. Effect of treatment on phosphorus loss during different crop and fallow periods. Figures in parentheses indicate the number of runoff events from the two plots represented in each of the treatments. For fallow 1991–1992 and 1993 there was not sufficient sediment to analyze for total phosphorus.

Crop-fallow period	Up and down slope	Across slope	Minimal	Standard
	g			
Potato 1989	124.6* (3)	1.5* (4)	88.6 (4)	37.6 (3)
Fallow 1989	23.6 (4)	6.7 (1)	9.9 (3)	20.35 (2)
Winter wheat 1989–1990	800.8 (51)	874.4 (46)	533.2 (49)	1142.0 (48)
Fallow 1990	0 (0)	0 (0)	0 (0)	0 (0)
Winter barley 1990–1991	6.0 (6)	0.4 (1)	1.4 (3)	5.0 (4)
Fallow 1991–1992	0 (2)	0 (0)	0 (0)	0 (2)
Sugar beet 1992	99.2* (29)	9.3* (12)	43.9 (19)	51.8 (22)
Fallow 1992	149.3 (33)	134.2 (27)	136.1 (31)	147.4 (29)
Winter wheat 1992–1993	1.63* (6)	0* (0)	0.9 (4)	0.7 (2)
Fallow 1993	0 (1)	0 (0)	0 (1)	0 (0)
Winter barley 1993–1994	85.3 (16)	15.8 (5)	6.6 (8)	94.5 (13)

* Significant at the 0.05 probability level; other treatments show no significant difference.

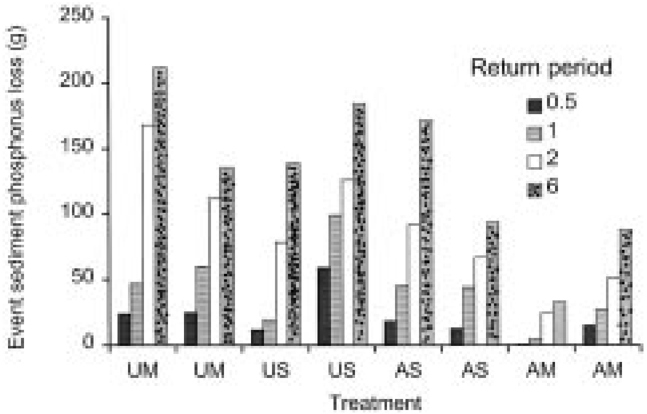

Fig. 9. Sediment P loss for events with return periods of 0.5, 1, 2, and 6 yr, for each of the plots of the Woburn Erosion Reference Experiment. U = cultivations up and down the slope, A = cultivations across the slope, M = minimal tillage with residues retained, and S = standard tillage with residues removed.

from the soil surface or the outer layers of aggregates, it leaves a coarser protective layer (Kinnell and Cummings, 1993), which is only removed to expose more P-rich material by the greater flow energies associated with higher discharge rates.

CONCLUSIONS

As the finer-sized fractions of the soil were preferentially lost from the plots of the Woburn Erosion Reference Experiment, the sediment was enriched in P. The enrichment was particularly associated with smaller erosion events. In larger events this selectivity was outweighed by the amount of sediment produced, so that more P was usually lost in higher-magnitude events than in those of lower magnitude. However, the lower-magnitude events were much more frequent and accounted for most of the P loss over the 6-yr observation period. This suggests that soil erosion control measures may need to be introduced more widely than previously thought if contamination of surface waters by P from agricultural sources is to be minimized.

Our results also suggest that the perception of erosion risk should be reassessed. Erosion is rarely considered to be a problem in the UK, and most attention is focussed on the problem of flooding (Boardman and Evans, 1994), usually associated with extreme events, such as those on the South Downs in October 1987 (Boardman, 1988). However, we suggest that small-magnitude erosion events have a disproportionately large potential to cause P pollution and have short return periods. All water erosion should therefore be treated as a potential threat to water quality if the resulting sediment is likely to reach surface water bodies. We suggest the use of cultivations on the contour and minimal tillage to mitigate this threat.

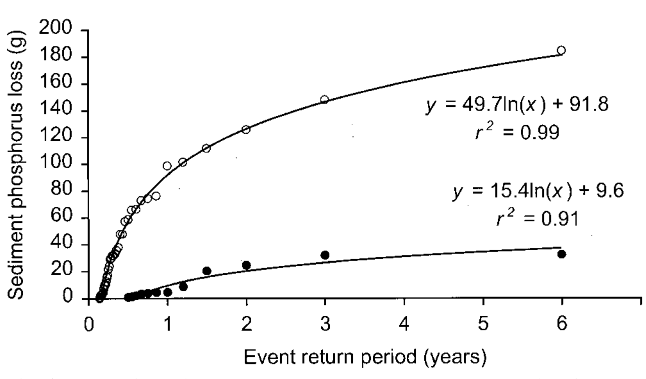

Fig. 10. Relationship between P loss and event return period for Plot 3, with across-slope minimal tillage (●) and Plot 7, with up and down–slope standard cultivation (○) in the Woburn Erosion Reference Experiment.

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