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Mobilisation and Transport of Sediment-Associated Phosphorus by Surface Runoff

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Abstract Surface runoff transporting sediment with high phosphorus (P) concentrations has been identified as a major hydrological pathway for sediment-associated P delivery to surface waters and is considered a major threat to water quality, due to the ability of P to cause eutrophication in fresh water. Not all P-rich sediment that is mobilised by erosion will however be delivered directly to the channel. Some may instead be deposited in intermediate storage away from its source area. The aim of this contribution was to determine the influence of land use and soil type on the P content of surface runoff sediment and sediment deposited in intermediate storage and was undertaken in the largely agricultural and rural catchments of the Rivers Frome and Piddle in Dorset, UK. The study formed part of a larger investigation of hydrological and hydrogeochemical processes and fluxes in lowland permeable catchments in the UK (LOCAR). Soil samples were collected from the main land use types; freshly deposited sediment was sampled from ditches, hedge boundaries and depressions in fields, and sediment-laden runoff was collected during heavy rainfall events. The concentrations of total phosphorus (TP) and the P fractions found in the surface runoff sediment were significantly different from those measured in the original source soils, with a greater degree of enrichment associated with surface runoff sediment from cultivated land than from pasture land. For cultivated land, concentrations of TP and the P fractions in deposited sediment were higher than those in the original source material, while for pasture soils, concentrations of TP and the P fractions tended to be lower than in the original source soils. The relative importance of the P fractions associated with surface runoff sediment and sediment deposits also differed from that for the original soil samples. Surface runoff sediment was finer than source pasture and cultivated soils, reflecting the particle size selectivity of sediment mobilisation and transport. Soil physical properties and land use can both influence the P content of surface runoff and deposited sediment.

Keywords Runoff · Sediment · Land use · Erosion · Transport · Selectivity · Phosphorus · Enrichment · Deposited sediment · Runoff sediment · Soil type

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1 Introduction

Surface runoff transporting sediment with high P concentrations that reaches the channel network has been identified as a major hydrological pathway for P delivery to surface waters, and, depending on its chemical composition, may have a detrimental impact on water quality. Its impact on water quality will however, be strongly influenced by the fractionation of the sediment-associated P, since only a proportion of the P will be available to in-stream organisms. Existing studies have shown that the proportion of algal available P in sediment can vary from 7% to 50% (Huettl et al. 1979; Uusitalo et al. 2001).

The amount and fractionation of P transported by surface runoff generated within the primary source areas will be dependent on two key factors: firstly soil biochemical processes, which control the amount and forms of P available for transport, and secondly, hillslope hydrology, which will define the mechanism and pathways for mobilisation and transfer. In addition, P transport from land to water will be influenced by land management practices, rainfall characteristics, soil properties and antecedent moisture conditions (Heathwaite and Dils 2000). To explain the significance of each of these factors for sediment-associated P transport in surface runoff, cultivated land in regular receipt of fertiliser is accepted as producing runoff that is more P-enriched than non-cultivated, more “natural” land use types (Sharpley and Smith 1990). Sediment-associated P export during storm events is known to increase with the amount and intensity of rainfall (Fraser et al. 1999). Because soil erosion is generally a size selective process (Sharpley and Smith 1990), the finer particles are often preferentially eroded and detached from their source, and finer particles are known to have higher P concentrations than coarser material, due to their increased specific surface area (Stone and English 1993). Further enrichment of particulate P may also occur during transport by runoff, due to adsorption of dissolved P (Sharpley et al. 1981). Surface runoff is more likely to occur if the soil is already close to saturation prior to rainfall, and in such a state, soil particles will be easily detached and mobilised.

It is well known that the spatial distribution of sediment sources is not uniform across catchments, and that not every field in a catchment should be regarded as a source area for sediment and its associated P load. Instead, the most critical source areas for sediment-associated P in catchments will be hydrologically active areas that intersect easily erodible zones, where soil P concentrations are high (Pionke et al. 2000), therefore source areas are frequently concentrated in relatively small definable areas located close to the stream network (Russell et al. 2001). Not all sediment however that is detached and transported from its source area will be delivered to the river channel system (Walling 1983). Very often mobilised sediment will be re-deposited, perhaps on encountering an obstacle such as dense vegetation or a hedge boundary. In some cases the runoff transporting the sediment may not possess sufficient energy to convey the mobilised sediment from the source to the river system due to large distances frequently involved. Equally the runoff may infiltrate some distance from its source, leading to deposition of sediment, and also potentially introducing P-rich sediment to areas where soil P concentrations are naturally lower.

The recently adopted EU Water Framework Directive (EU 2000) requires that good ecological status must be established in streams and lakes during the coming one to two decades. However, delivery of sediment-associated P to streams in surface runoff could prevent the achievement of good ecological status, as defined by the Water Framework Directive, due to the ability of the bio-available fraction of P to cause eutrophication in both rivers and lakes (Kronvang et al. 2003).

Recognising this knowledge gap and the significance of sediment-associated nutrient transfers to river channels in terms of their potential to impact on the fresh water environment, the purpose of this investigation was to contribute to an improved understanding of phosphorus dynamics in sediment entrained in surface runoff. More specifically, the aim of this present study was to examine the influence of land use and soil type on the content and fractionation of P in surface runoff sediment and deposited sediment. The main objectives of this study were:

1. To examine and compare the content and fractionation of P in soils from cultivated and pasture land in the study catchments with that of the sediment both (a) entrained in runoff from cultivated and pasture land during rainfall events,

and (b) re-deposited before reaching the stream network

2. To evaluate changes noted between the P content and fractionation of the source soils and the sediment entrained in runoff and re-deposited sediment

2 Methods

2.1 Study Catchments

Two lowland groundwater dominated catchments, the Frome (425 km^2) and the Piddle (183 km^2) in Dorset (Fig. 1), forming part of the NERC LOCAR (Lowland Catchment Research) programme, were selected for the investigation. Both catchments are primarily underlain by chalk (ca 65% of their area), although outcrops of Jurassic limestone and Cretaceous Upper Greensand occur in the headwaters, and Tertiary sands and gravels are found in the lower reaches. The headwater areas of both catchments are dominated by chalk outcrops, with steep slopes and maximum elevations of 264 m and 273 m a.s.l., in the Frome and Piddle catchments, respectively. In contrast, the lower reaches of both catchments are characterised by gentle relief and extensive well-developed floodplains. The soils present in the areas sampled are mainly from the Blewbury, Batcombe and Andover associations. Blewbury soils are typically well drained brown calcareous earths (sand 24%; silt 40%; clay 36%); Batcombe soils are brown, slightly stony silt loams (sand 20%; silt 42%; clay 38%) while Andover soils are dark brown, slightly stony silty clay loams (sand 12%; silt 43%; clay 45%). Agricultural land accounts for >80% of each of the catchments, and land use is dominated by pasture and cereal cultivation. The mean annual precipitation is ~932 mm in the Frome and ~888 mm in the Piddle. The average daily flows at the lowest gauging stations in the Frome and Piddle catchments are 6.44 and 2.46 m^3 s^{-1}, respectively. The mainly rural catchments are noted as being of high amenity value, with the Frome reported to be one of the last natural chalk stream salmon fisheries in the UK.

2.2 Sampling Methods

Discrete surface soil samples were randomly collected from areas under cultivation (n=116) and long-term pasture (n=114) in the study catchments, to provide samples that were representative of the main land use types found in the study catchments and of topsoil that was likely to be mobilised by erosion processes. Soils sampled were from the Blewbury, Batcombe and Andover associations. Material was collected from the top 2 cm of the soil profile, using a graduated stainless steel trowel, and placed in labelled

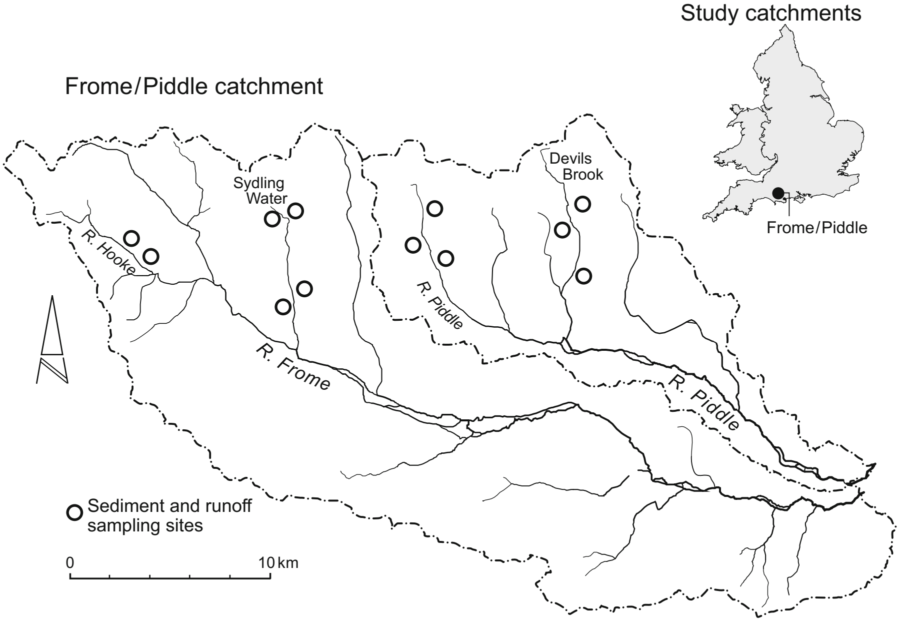

Fig. 1 The location of (*a*) the sub-catchments in which soils, surface runoff and deposited sediment were sampled in the Frome and Piddle catchments and (*b*) the locations of the Frome and Piddle catchments

polythene bags. Discrete samples of surface runoff ($n=15$) were also collected manually during rainfall events in 500 ml plastic bottles. Runoff sampling sites were chosen along the main channel of the River Piddle and in the sub-catchments of the Sydling Water, River Hooke and the Devil's Brook, in a subsample of the cultivated and pasture fields that had been sampled for source material, and which provided sources of surface runoff in heavy rainfall events (Fig. 1). Samples were collected during three storm events occurring between December 2003 and February 2004, and, in total, ten samples were collected from pasture fields and 15 from cultivated fields during the three events sampled. To represent sediment that had been mobilised from its source area but re-deposited elsewhere before reaching the channel network, samples of recently deposited sediment ($n=84$), easily identified due to its visual appearance and high moisture content, were collected from depressions in fields and along the hedge boundaries and ditches of a selection of the cultivated and pasture fields which had been sampled for potential source soils and surface runoff. The deposited sediment samples were collected on the days following the rainfall events sampled for surface runoff, using the same procedure as was used for sampling source material.

2.3 Laboratory Analysis

On return to the laboratory, the samples of surface soil and deposited sediment were oven dried at 40°C. The bottles containing runoff samples were left to settle. The supernatant was then siphoned off and the remaining water and sediment were transferred to a centrifuge bottle and centrifuged at 2,500 rpm for 1 h. The sediment recovered was then transferred to a plastic pot and freeze-dried using a Christ freeze drier. In order to facilitate comparison between samples, once dry, all soil, surface runoff sediment, and deposited sediment samples were gently disaggregated using a pestle and mortar and then dry sieved to <63 μm. The total phosphorus (TP) and inorganic phosphorus (IP) contents of the <63 μm fraction were determined by UV visible spectrophotometry following sequential chemical extraction with hydrochloric acid and sodium hydroxide using the molybdenum blue method described by Mehta et al. (1954), while the organic phosphorus (OP) content was calculated by subtraction. The algal available fraction (AAP) was extracted using 0.1 M sodium hydroxide, as described by Dorich et al. (1985). This chemical extraction method was chosen, because it was found by Dorich et al. (1985) to be significantly correlated with 2- and 14-day available phosphorus for algae, thereby indicating that NaOH-extractable phosphorus could be used to estimate both short- and longer-term available phosphorus in sediments. The specific surface area (SSA) of the soil, surface runoff sediment and deposited sediment samples was estimated from the grain size distribution (assuming spherical particles) measured using a Coulter LS130 laser diffraction granulometer, after pre-treatment with 30% hydrogen peroxide to remove the organic matter, followed by ultrasonic dispersion. A selection of samples were analysed in duplicate for P and SSA to check for consistency. The resulting datasets were examined for significant contrasts using the Mann Whitney non-parametric statistical test and all statistical differences mentioned are at the $P<0.05$ level of significance.

3 Results and Discussion

3.1 The Phosphorus Content of Pasture and Cultivated Topsoils

Table 1 presents summary information on the TP content of the sampled source soils, which shows that the TP content was highest in pasture soils and lowest in cultivated soils. Lower values of TP associated with cultivated soils, similar to what were observed in this study, have also been reported by Wallbrink et al. (2003), and are likely to reflect P export with crop material, or mixing of surface soil with subsoil of lower TP concentrations by cultivation.

Considering the relative contributions of the P fractions to the TP content of topsoil, IP was the dominant fraction in soil samples taken from cultivated land, representing 53% of the TP content. The percentage contribution of AAP to TP (29%) was also highest in cultivated land, and the higher contribution of both IP and AAP to TP associated with cultivated soil reflects the regular and intensive application of fertilisers. In contrast, the OP fraction was dominant in pasture soils, accounting for 68% of the TP content, and this higher OP contribution to TP in pasture soils reflects their higher organic matter content and the addition of organic material from animal manure.

Table 1 Mean values for TP, IP, OP and AAP and SSA for topsoil collected from different land use and soil types in the catchments of the Rivers Frome and Piddle and comparison of the mean TP, IP, OP and AAP concentrations for surface runoff sediment with equivalent values for source soils

	Soil type	Cultivated source	Pasture source	TP	IP	OP	AAP	% IP	% AAP	SSA
				419 (18)	224 (15)	194 (14)	124 (14)	53	29	0.383 (0.010)
Sydling	Andover	Runoff		1,834 (195)	1,253 (143)	581 (65)	200 (10)	61	10	0.995 (0.061)
Piddle	Batcombe	Runoff		4,584 (2,290)	2,706 (1,266)	1,878 (1,206)	232 (29)	62	13	0.857 (0.108)
				919 (37)	290 (20)	629 (28)	97 (11)	32	10	0.404 (0.010)
Hooke	Blewbury	Runoff		2,543 (404)	1,587 (284)	957 (137)	713 (149)	62	28	0.679 (0.154)
Sydling	Andover	Runoff		1,357 (182)	831 (90)	527 (92)	41 (25)	68	3	0.596 (0.072)

Figures in parentheses show one standard error of the mean.

3.2 The Phosphorus Content of Sediment Recovered from Surface Runoff

Summary information on the TP concentrations, P fractions and SSA values associated with the <63 μm fraction of surface runoff sediment is presented in Table 1. The TP concentrations associated with this sediment were much higher than those found in the cultivated and pasture source soils, however there was a greater increase associated with the TP concentrations in surface runoff sediment from cultivated land than from pasture land. The TP concentrations measured in surface runoff sediment from cultivated land and from the pasture fields in the Hooke catchment were significantly different from those in the original source soils, while those in surface runoff sediment from pasture fields in the Sydling catchment were not significantly different from those in the source soils (Table 2).

The increased TP concentrations associated with surface runoff sediment relative to those in the source soils were mostly mirrored by increases in the concentrations of IP, OP and AAP (Table 1), with the exception of the OP and AAP fractions in surface runoff sediment from the pasture fields in the Sydling catchment. IP and OP concentrations in surface runoff sediment from both pasture and cultivated land differed significantly from the IP and OP concentrations in the corresponding source soils at the 95% level (Table 2), but only the AAP content of surface runoff sediment from pasture land in the Hooke catchment was significantly different from the AAP concentration in the source soils (Table 2).

The contributions of the various P fractions to TP associated with the surface runoff sediment also differed from those for the original soil samples, as shown in Table 1. When compared to the source soils, the mean percentage contribution of the IP fraction to TP in surface runoff sediment from both pasture and cultivated land increased, while the mean percentage of AAP to TP decreased in all cases apart from the surface runoff sediment from the Hooke pasture fields, where the mean percentage contribution to TP almost doubled.

Calculation of an enrichment ratio, defined by Sharpley (1980) as the ratio of the phosphorus concentration in surface runoff sediment to that in the source soil, gives values of greater than 1 for TP in all cases (Table 3). Enrichment values for the P fractions were mostly greater than 1 for this study,

Table 2 Significant differences between the concentrations of TP and P fractions and SSA in source soils and sediment in surface runoff as determined by use of the Mann Whitney test

	Cultivated source	Pasture source	TP	IP	OP	AAP	SSA
Sydling	Runoff		**0.003**	**0.003**	**0.005**	0.0972	**0.0161**
Piddle	Runoff		**0**	**0**	**0**	0.06	**0.0003**
Hooke		Runoff	**0.0009**	**0.0007**	**0.0271**	**0.0011**	**0.0141**
Sydling		Runoff	0.1063	**0.0217**	0.058	0.3239	**0.0359**

Significant differences at the 95% level are shown in bold type.

Table 3 Enrichment ratios for fractions of phosphorus and SSA for sediment in surface runoff samples when compared to source soils

	Soil type	Cultivated soils	Pasture soils	TP	IP	OP	AAP	SSA
Sydling	Andover	Runoff		4.38	5.59	2.99	1.61	2.59
Piddle	Batcombe	Runoff		10.94	12.08	9.68	1.87	2.24
Hooke	Blewbury		Runoff	2.77	5.47	1.52	7.35	1.68
Sydling	Andover		Runoff	1.48	2.87	0.837	0.42	1.48

with the exception of the OP and AAP fractions in runoff sediment from the pasture fields in the Sydling catchment, showing that there is generally enrichment of TP and all the P fractions in sediment recovered from surface runoff relative to the source soil. The degree of enrichment, associated with surface runoff sediment from cultivated land was generally more than that noted for pasture land.

The higher concentrations of both TP and the P fractions measured in sediment recovered from surface runoff and the enrichment ratios presented in Table 3 are consistent with the findings of Sharpley (1985), who also reported similar increases in TP concentrations in eroded sediment entrained in surface runoff when compared with TP concentrations in source material. Further, the higher TP enrichment associated with sediment recovered from surface runoff from cultivated land than from pasture areas found in this study conforms to the findings of Sharpley et al. (1981), who reported that sediment in runoff from cultivated soil was more enriched in P than sediment in runoff from pasture areas. The increase in TP concentrations seen in the current study is most likely to reflect differences in the particle size distributions of the source soil and the sediment in the runoff, and the increased proportion of finer sediment in the runoff, although it may also reflect adsorption of P from the dissolved phase in the runoff during transport.

The concentrations of the P fractions measured also provide evidence of enrichment in most cases, supporting the findings of Sharpley (1985) and Dorich et al. (1984), who both reported enrichment for the P fractions measured in sediment recovered from surface runoff, with the latter authors noting a higher degree of IP enrichment associated with sediment from cultivated fields than from pasture land. The AAP fraction also showed significant enrichment in sediment in surface runoff collected from cultivated soils, which again agrees with the findings of Sharpley et al. (1992).

3.3 The Phosphorus Content of Deposited Sediment

Information on the mean P concentrations in deposited sediment is presented in Table 4. Comparison of the TP concentrations in source soils and deposited sediment shows that the TP concentrations in deposited sediment from cultivated soils were higher than the TP concentrations found in cultivated source soils, and that the TP concentrations in deposited sediment differed significantly from those in cultivated source soils, due

Table 4 Mean values for TP, IP, OP and AAP and SSA for topsoil collected from different land use and soil types in the catchments of the Rivers Frome and Piddle and comparison of the mean TP, IP, OP and AAP concentrations in deposited sediment with equivalent values for source soils

	Soil type	Cultivated source	Pasture source	TP	IP	OP	AAP	% IP	% AAP	SSA
				419 (18)	224 (15)	194 (14)	124 (14)	53	29	0.383 (0.010)
Hooke	Blewbury	Deposited sediment		980 (83)	226 (19)	755 (88)	26 (5)	25	2	0.412 (0.025)
Sydling	Andover	Deposited sediment		756 (50)	313 (23)	443 (33)	44 (6)	41	6	0.543 (0.016)
Piddle	Batcombe	Deposited sediment		643 (55)	234 (25)	409 (33)	46 (12)	38	2	0.6217 (0.016)
				919 (37)	290 (20)	629 (28)	97 (11)	32	10	0.404 (0.010)
Hooke	Blewbury	Deposited sediment		503 (74)	198 (37)	304 (40)	36 (6)	32	7	0.356 (0.043)
Sydling	Andover	Deposited sediment		676 (90)	252 (43)	424 (50)	31 (5)	37	5	0.651(0.035)
Piddle	Batcombe	Deposited sediment		1,105 (101)	282 (26)	823 (94)	42 (6)	42	6	0.390 (0.026)

Figures in parentheses show one standard error of the mean.

to the increase in concentrations in the deposited sediment relative to the source soils (Table 5). There was no consistent trend towards either an increase or decrease in TP concentrations for deposited sediment from pasture soils, as the TP concentrations in deposited sediment from pasture fields in the Hooke and Sydling catchments were lower than those in the pasture source soils, and the TP concentrations in the deposited sediment from pasture soils in the Piddle catchment were higher than those in the source soils. For pasture soils, only the lower TP concentrations observed in deposited sediment in the Hooke catchment were significantly different from those in the pasture source soils (Table 5).

Other authors have reported variation between the TP content of transported and re-deposited sediment and the original source soils and, similar to this present study, both higher and lower TP concentrations have been found. Higher TP concentrations and higher SSA values for both transported and re-deposited sediment were reported by Sharpley (1985), who concluded that eroded and transported sediment, and thus deposited sediment, were richer in P than the source soil, due to the selective erosion of finer clay size particles. Scherer (2000) and Nguyen and Sukias (2002) also noted that sediment transported from its parent location and re-deposited elsewhere was enriched in P, with Scherer (2000) reporting an enrichment ratio of 1.7 between the source soil and sediment re-deposited away from the source. In contrast, Fullen et al. (1996) reported that deposited sediment had lower P concentrations than parent soil in a study carried out in East Shropshire, UK, which probably reflects the preferential deposition of coarse particles, since coarser sediment can be expected to be characterised by lower P concentrations. While the deposited sediments from pasture land in the Hooke and Piddle catchments were coarser than the original source soils, only in the case of the deposited sediment in the Hooke catchment was the TP concentration lower than that observed in the original pasture source soil.

Mean concentrations of the P fractions and the contributions of IP and AAP to TP in deposited sediment are presented in Table 4. The IP concentrations in deposited sediment from both cultivated and pasture soils showed little change from those measured in the source soils, with only a slight increase and decrease noted when compared to the IP content of cultivated and pasture soils respectively. Further, there was no significant difference between the IP concentrations in the cultivated and pasture source soils and the equivalent sediment deposits, except in the case of the sediment deposits in the Sydling catchment from both cultivated and pasture land (Table 5). The percentage contribution of the IP fraction to TP in the sediment deposits was less than that for the original soils from cultivated land, but higher for pasture soils. The OP concentrations in deposited sediment from cultivated land were significantly higher than those in the original source soils (Table 5), while for pasture land there was no consistent trend towards an increase or decrease in the OP concentrations of deposited sediment. The increases noted in the OP concentrations in deposited sediment from cultivated soils, when compared to the OP concentrations in source soils, may reflect enrichment due to P sorption from vegetation during mobilisation and transport, as vegetation is known to be a nutrient pool and a source of phosphorus (Lam et al. 1997). The mean concentrations of AAP associated with deposited sediment from both cultivated and pasture fields were significantly lower than those in the equivalent source soils (Table 5). Also the

Table 5 Significant differences between the concentrations of TP, P fractions and SSA measurements of deposited sediment and source soils as shown by use of the Mann–Whitney statistical test

	Cultivated source	Pasture source	TP	IP	OP	AAP	SSA
Hooke	Deposits		**0**	0.795	**0**	**0.0014**	0.2568
Sydling	Deposits		**0.0033**	**0.0033**	**0.0053**	**0.0161**	**0.0161**
Piddle	Deposits		**0.0002**	0.6777	**0**	**0.0302**	0
Hooke		Deposits	**0.0022**	0.1995	**0**	**0.0117**	0.3237
Sydling		Deposits	0.1063	**0.0217**	0.5753	**0.0323**	**0.0359**
Piddle		Deposits	**0.0294**	0.7767	**0.0025**	**0.0272**	**0.0242**

Significant differences at the 95% level are shown in bold type.

Table 6 Enrichment ratios for fractions of phosphorus and SSA for deposited sediments when compared to source soils

	Soil type	Cultivated soils	Pasture soils	TP	IP	OP	AAP	SSA
Hooke	Blewbury	Deposited		2.34	1.01	3.89	0.21	1.08
Sydling	Andover	Deposited		1.8	1.4	2.28	0.35	1.42
Piddle	Batcombe	Deposited		1.53	1.04	2.11	0.37	1.62
Hooke	Blewbury		Deposited	0.55	0.68	0.48	0.37	0.88
Sydling	Andover		Deposited	0.01	0.87	0.67	0.32	1.61
Piddle	Batcombe		Deposited	1.2	0.97	1.31	0.43	0.97

percentage contribution of the AAP fraction to TP decreased from 29% to between 2% and 6% for the deposited sediment from cultivated soils, and from 10% to between 5% and 7% for the deposited sediment from pasture land.

The tendency towards an increase in the TP concentrations and concentrations of the IP and OP fractions of deposited sediment from cultivated land with respect to the source soil suggests that land use effects had a strong influence on the P content of deposited sediment rather than soil physical properties. The lack of a trend towards either an increase or decrease in the concentrations of TP and the P fractions for deposited sediment from pasture land suggests that, for this study, soil type and soil physical properties, rather than land use effects, were a strong influence on the P content of deposited sediment from pasture land.

Consideration of the enrichment ratio values, presented in Table 6, shows that there was generally enrichment of TP and the P fractions for deposited sediment from cultivated soils, with enrichment observed for all the P fractions in deposited sediment from cultivated land, except for AAP. In contrast, deposited sediment from pasture soils tended to be depleted, as shown by the values lower than 1. Table 6 shows that there was only enrichment of TP and OP in deposited sediment from pasture land in the Piddle catchment.

3.4 The Specific Surface Area of Sediment in Surface Runoff and Deposited Sediment

Mean values of SSA associated with the sediment recovered from surface runoff showed an increase when compared to SSA values for source soils (Table 1), which serves to highlight the selectivity of the erosion and transport process, and confirms that erosion is a size selective process, where finer soil particles are preferentially eroded and transported from the source area, as was also reported by Sharpley and Smith (1990) and Sharpley (1985). Comparing the SSA of sediment recovered from surface runoff from cultivated land and pasture land, a greater degree of fining was associated with sediment in runoff transported from cultivated land, as shown by the higher enrichment ratio for sediment from cultivated soils (Table 3). When tested statistically, the SSA values for sediment in surface runoff from both cultivated and pasture land were significantly different from those for the original source soils (Table 2).

The mean SSA values for the deposited sediment from cultivated land were greater than those found in the source soils, but less than those obtained for sediment in surface runoff, confirming the preferential mobilisation of finer sediment from the source cultivated soil and preferential deposition of the coarser fractions of the transported sediment. Deposited sediment from cultivated source soils were significantly finer than the source cultivated soils (Table 5), except for the deposited sediment in the Hooke catchment which was only slightly finer than the original source soil. In contrast, there was no clear pattern for the SSA values observed for the sediment deposits from pasture land, with higher and lower values being recorded when compared to the source soils. The SSA values measured, however, reflected the sand, silt and clay contents of the source soils, with the finest deposited sediment deriving from the Andover soil, which had the lowest sand, and highest clay, content, and the coarsest deposited sediment deriving from the Blewbury soil, which had the highest sand content. The lower SSA values in the sediment deposited from the Blewbury and Batcombe soils in the Hooke and Piddle catchments, when compared to the source soils, demonstrate the deposition of coarser material and preferential transport of finer material in runoff. Comparison of the particle size properties of the deposited sediment with those of surface runoff sediment also showed a significant difference (Mann Whitney, $P=0.0018$, sig level <0.05), with the sediment recovered from surface runoff being much finer than the deposited sediment in all cases.

The significant fining in particle size observed from cultivated source soil to both deposited sediment and surface runoff sediment may, to some extent, explain the higher TP concentrations in surface runoff sediment from cultivated and pasture land and in the deposited sediment from cultivated land relative to the source material, due to the positive relationship between SSA and TP concentrations. SSA values however do not explain the TP concentrations in deposited sediment from pasture land. As for cultivated soils in this study, Sharpley (1985) and Scherer (2000) found that soil particles mobilised, transported and deposited downslope were generally finer than the source soils.

4 Conclusion

The results presented above serve to emphasise the differences in the concentrations of both TP and its fractions in soils from different management regimes in the study area. Comparing the different soils, intensively managed cultivated soils tended to have a lower TP content, yet a higher proportion of IP and AAP, while in pasture fields the soils were characterised by a higher proportion and content of OP and lower concentrations and contributions from AAP.

Examination of the P concentrations of surface runoff sediment from both cultivated and pasture land has shown that the TP concentrations, and those of the P fractions, can increase during transport. Surface runoff sediment recovered from cultivated land showed a greater degree of enrichment relative to the source soils than that recovered from pasture land. The findings from this study emphasise the need to consider not only the TP concentrations, but also the constituent P fractions in sediment in surface runoff, because as well as showing increases in concentration when compared to the original material, the relative contributions of the various fractions were significantly altered, which may have important implications for the bio-availability of the P. Sediment recovered from surface runoff was also much finer than the source soils and the sediment deposits, providing further evidence of the selectivity of the erosion, transport and deposition process.

This study also shows that soil type and land use can be important influences in the P content of deposited sediment. P concentrations in deposited sediment from cultivated source soils tended to be higher than the source soils irrespective of soil type, suggesting that land use is an important influence on the P concentrations of deposited sediment from cultivated soils. The high variability noted between the P concentrations in deposited sediment from pasture source soils suggests that, for this study, soil type and soil physical properties were a more important influence than land use in the P concentrations of deposited sediment from pasture source soils. The SSA values of deposited sediment from pasture soils reflect the grain size distribution of the original source soils to a greater degree than the deposited sediment from cultivated soils. Further, deposited sediment from pasture soils tended to be coarser than the source material, indicating deposition of coarser material and selective transport of the finer fractions.

This study confirms that P-rich sediment has the potential to be transported downslope towards watercourses during heavy rainfall events, and over successive events, may even enter the channel network where land is hydrologically connected. Even if they are individually small, such inputs, when aggregated on a catchment-wide basis, could lead to significant quantities of P being introduced into the channel network. Depending on its fractionation and the potential for transformations that may increase P availability during transport, inputs of P-rich sediment in surface runoff could cause degradation of a receiving watercourse, resulting in, and maintaining, eutrophic conditions if sustained over a prolonged time period. Further, the increased P concentrations found in deposited sediment relative to those in cultivated soils demonstrates that the deposition of sediment being transported downhill could lead to the introduction of additional P to areas where the soil P concentrations are naturally lower. This may have implications for land management decisions, for example, buffer strips could be placed at intervals on the hillslopes so as to prevent arrival of P rich sediment in the riparian zone. The information presented therefore emphasises the need to develop sound land management practices and guidelines, concerned not only with crop performance but which also address environmental concerns, such as the reduction of soil and associated P losses from agricultural land.

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