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The role of soil phosphorus in controlling sediment-associated phosphorus transfers in river catchments

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Abstract Many of the models used to determine phosphorus (P) transfers within river catchments use soil-P concentrations as one of the main input data sets. Such soil-P values are often based on bulked soil cores. To test the validity of using such data, depth profiles of total-P and Olsen-P were determined for arable and grassland fields in the catchment of the Hampshire Avon, UK. For the soils under grassland, maximum soil-P values occur at or near the surface and decrease with depth. For soils under arable, total-P values are broadly constant within the plough layer, whereas for Olsen-P maximum values are located at or near the surface, below which values are broadly constant to the plough depth. These findings have important implications for the use of bulked soil-P data to represent the concentrations of P at the soil surface, particularly for modelling P transfers associated with soil erosion and overland flow.

Key words fluvial sediment; models; NSI database; phosphorus; PSYCHIC; soil profiles

INTRODUCTION

Phosphorus (P) is often cited as the main nutrient causing eutrophication in rivers and lakes (Correll, 1998). In most catchments, much of the phosphorus being delivered to, and transported by, rivers is associated with fine-grained sediment (Russell *et al.*, 1998; Owens & Walling, 2002). In order to help reduce the extent of eutrophication in river catchments, there has been a concerted effort in many countries to reduce the delivery of P to rivers. To date, most effort has focused on reducing the delivery of P from point sources such as sewage treatment works (STWs), and available evidence suggests that in some cases this may be working. Thus Owens & Walling (2003) used flood plain deposits to reconstruct changing P transfers through rivers in Yorkshire, UK, over the last approx. 100 years. They demonstrated that for a river receiving inputs from STWs and other point sources, the P content of fluvial sediment had decreased over the last approx. 10 years, whereas there was no similar evidence of a decrease in P levels in rivers draining rural catchments that received primarily non-point, or diffuse, sources of P. In catchments where there has been a reasonable amount of success in controlling point sources of P, increasing attention is focusing on reducing P delivery to rivers from diffuse sources.

Because of the inherent complexities associated with trying to understand and control the delivery of P to surface waters from diffuse sources in all but the simplest (and usually smallest) catchments, a variety of models have been developed recently in order to predict the extent and spatial distribution of P transfers within land and river systems. In the UK, such models include the Export Coefficient Model (Johnes, 1996), the P-Expert System Model (Harrod & Fraser, 1999) and the Phosphorus Indicators Tool (Heathwaite *et al.*, 2003). A new model currently being developed by the authors and colleagues to estimate the delivery of P from land to rivers in the UK is the PSYCHIC (Phosphorus and Sediment Yield Characterization) model. Many of these models, including PSYCHIC, and other similar models worldwide, require input values of the P content of soils. In most catchments, a large proportion of the diffuse P delivered to waters is via surface pathways and is associated with soil erosion and sediment transfers by overland flow (Haygarth *et al.*, 1998; Harrod & Fraser, 1999; Heathwaite *et al.*, 2003). Consequently, accurate values of the P content of the uppermost layers of topsoil (i.e. upper few centimetres) is crucial for these models to be able to determine P delivery to rivers and lakes via surface pathways. However, to date, many models have used lumped soil-P data. Thus, for example, the soil-P input data for the Phosphorus Indicators Tool and the PSYCHIC models are based on the National Soil Inventory (NSI) database, which represents bulked values for the 0–15 cm topsoil layer for samples collected at 5 km grid intervals throughout England and Wales between 1978 and 1983 (McGrath & Loveland, 1992). In consequence, the soil-P values used in these models represent the average P content of soil within the upper 15 cm of the soil profile. Studies (e.g. Haygarth *et al.*, 1998; Withers *et al.*, 2001) have, however, shown that in uncultivated soils there tends to be a decrease in soil-P concentrations with depth, with maximum values at, or close to, the surface. Although the depth profile of P in cultivated soils is expected to be more homogeneous (due to soil mixing during tillage), it is still uncertain how representative a bulked value for 0–15 cm depth is of P concentrations in the upper few centimetres.

This paper presents depth profiles of P (both total and Olsen) in agricultural fields for different soil types in one of the PSYCHIC study catchments, and examines the effect of these depth profiles on the values of soil-P to be used in the PSYCHIC model for determining (particulate) P delivery to rivers in this catchment.

STUDY AREA AND METHODS

The Hampshire Avon is a large catchment (~1700 km^2) located in the counties of Wiltshire, Dorset and Hampshire in southern England. The upper catchment is characterized by rolling chalklands and sheltered river valleys and includes the arable landscape of Salisbury Plain. For the catchment as a whole, land use is dominated by arable cropping (33%) and permanent grassland (26%), with temporary grassland, woodland and lowland heath occupying 19, 9 and 3%, respectively.

Detailed soil-P profiles were determined for four dominant soil types within the Hampshire Avon catchment (Table 1). Soil samples were taken in both arable (for all four dominant soil types) and permanent grassland (for two of the soil types) fields. For two of the soil types (the typical brown calcareous earth and the typical argillic brown earth) it was difficult to find good examples of agricultural soil profiles, without any history of disturbance in the last few decades, and consequently grassland soil-P profiles were not determined for these soil types. To prevent profile compaction, which can occur using augers, a soil pit was dug to expose the profile face. Soil samples were collected by excavating into the profile face delineating samples in 1 cm depth increments down to 8 cm and then in 2 cm increments down to 20 cm (grassland) and 30 cm (arable).

Soil samples were air-dried, broken up and passed through a 2 mm sieve. Plant available P (Olsen-P) was determined by the Olsen's bicarbonate extractable P fraction method as described by Olsen *et al.* (1954). For total-P the air-dried soil was milled to a fine powder

Table 1 Description of the four soils examined in the Hampshire Avon catchment.

Site	Soil subgroup[†] Number	Name	Soil description[†]	Surface area of catchment (%)
Knoyle Down	3.43	Brown rendzina	Shallow well-drained calcareous silty soils	32
Mere Down	3.41	Humic rendzina	Shallow, mostly humose, well drained calcareous soils	14
Wilsford	5.11	Typical brown calcareous earth	Well-drained calcareous fine silty soils	10
Sunnyhill	5.71	Typical argillic brown earth	Well-drained fine and coarse loamy glauconitic soils	9

[†]Based on Avery (1980).

(<1 mm diameter) and the sodium hydroxide fusion method described by Smith & Bain (1982) was used to determine total phosphate. In both cases, the Murphy & Riley (1962) method was used to determine the Mo-reactive P in the extract.

RESULTS

Figure 1 shows plots of the depth profiles for both total-P and Olsen-P for the four arable and the two grassland fields. In the case of the depth profiles of P in the two soils under grassland (Knoyle Down and Mere Down) there are clear decreases in both total-P and Olsen-P with depth. For Knoyle Down, maximum values are at the soil surface (0–1 cm depth increment), whereas for Mere Down the maximum values of soil-P are in the 1–2 cm increment. These depth profiles are consistent with expectations for undisturbed grassland soils, with both the surface maxima and the marked decreases of soil-P with depth reflecting inputs of P to the soil surface due to additions of P-based fertilizers, manures and other artificial inputs, and the return of P in dead plants and storage in soil organic matter (Haygarth *et al.*, 1998). As expected, the decrease in values with depth is most pronounced with Olsen-P for both soil types.

In the case of the depth profiles of soil-P for the samples collected from the four arable fields there are some important trends. For the four profiles of total-P there is a trend of broadly consistent values from the surface to the depth of ploughing, which lies between 20 and 25 cm depth for these fields. Unlike the total-P profiles for the grassland fields, where maximum values are located at, or near, the soil surface, maximum values of total-P for the arable fields are not necessarily located near the soil surface and appear to be located anywhere within the plough layer. For the four profiles of Olsen-P, there are more complex depth distributions, with maximum values at, or near, the soil surface and with subsequent decreases in values with depth, which in turn are superimposed on a pattern of broadly constant values with depth. In other words, the effect of tillage processes on mixing the soil and associated P is still evident (particularly in the case of Sunnyhill) but there is also a trend of maximum values at the surface and marked decreases in Olsen-P values with depth, particularly within the upper 5–10 cm. The surface peak in Olsen-P values is consistent with the application of artificial sources of P (such as fertilizers) to the soil before tillage processes have mixed them thoroughly within the plough depth (i.e. between consecutive ploughing events).

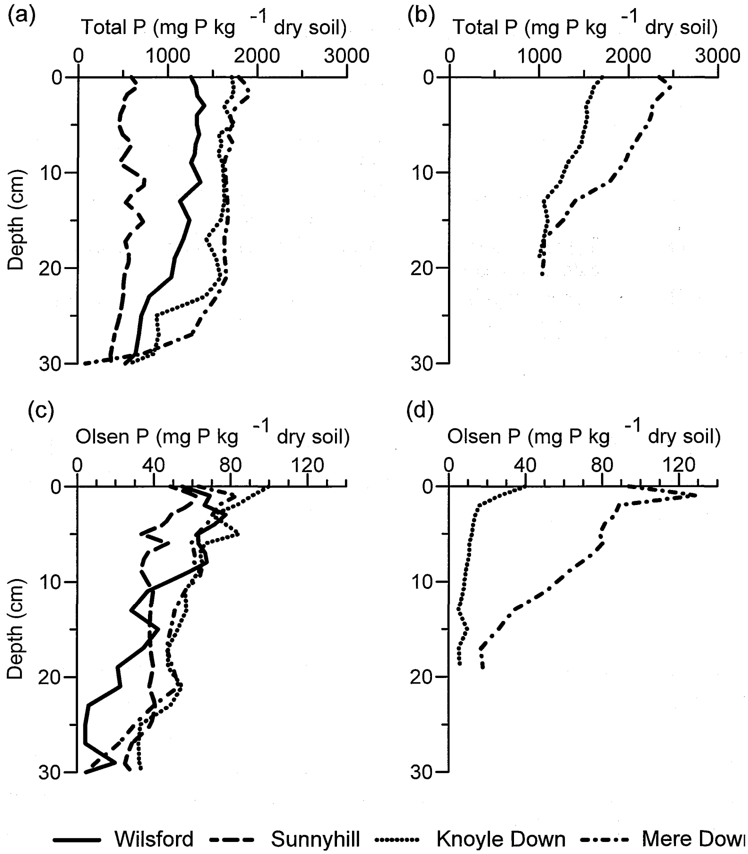

Fig. 1 The depth distribution of total-P in: (a) arable and (b) grassland soils, and Olsen-P in (c) arable and (d) grassland soils for key sites.

DISCUSSION

Tables 2 and 3 present summary statistics of soil-P for the soils under arable and grassland. For total-P (Table 2), values for the soil surface (expressed here as the average for the upper 2 cm) are in most cases greater than average values for the 0–15 cm depth. The depth 0–2 cm has been chosen to represent that layer of soil that is susceptible to rill and inter-rill erosion, and thus relevant to the modelling of P transfers associated with surface processes. The difference between values for the surface layers and the average for 0–15 cm depth are especially noticeable for the two grassland profiles, where surface and 0–15 cm values are 1658 and 1428 mg kg^{-1} and 2409 and 2040 mg kg^{-1}, respectively. Thus, surface values of total-P are 230 and 369 mg kg^{-1} higher than the average for the 0–15 cm depth, for the Knoyle Down and Mere Down sites, respectively. In the case of the soils under arable, surface concentrations of total-P are generally similar (i.e. differences are within the range 18–109 mg kg^{-1}) to the average values for the 0–15 cm depth. Clearly, for the soils examined here, the use of average (bulked) values for the 0–15 cm depth underestimates the total-P concentration of soil within the upper 2 cm of the profile by 14–15% and 4–10% in the case of the soils under grassland and arable (n = 3), respectively.

Table 2 Total-P concentrations (mean (0–15 cm), maximum and average for upper 2 cm of the profile) for the different soils under arable and grassland.

Site	Soil type	Land use	Total-P (mg P kg^{-1} dry soil)		
			Mean	Max	0–2 cm
Knoyle Down	Brown rendzina	Arable	1648	1733	1724
		Grassland	1428	1704	1658
Mere Down	Humic rendzina	Arable	1730	1904	1839
		Grassland	2040	2475	2409
Wilsford	Typical brown calcareous earth	Arable	1305	1408	1287
Sunnyhill	Typical argillic brown earth	Arable	568	670	632

Table 3 Olsen-P concentrations (mean (0–15 cm), maximum and average for upper 2 cm of the profile) for the different soils under arable and grassland.

Site	Soil type	Land use	Olsen-P (mg P kg^{-1} dry soil)		
			Mean	Max	0–2 cm
Knoyle Down	Brown rendzina	Arable	71.1	99.6	96
		Grassland	14.0	39.7	33
Mere Down	Humic rendzina	Arable	63.3	83.1	73
		Grassland	73.5	128.7	112
Wilsford	Typical brown calcareous earth	Arable	58.8	77.3	62
Sunnyhill	Typical argillic brown earth	Arable	43.3	61.9	55

In the case of Olsen-P (Table 3), there is a similar pattern. For soils under both grassland and arable, values of Olsen-P are greater in the 0–2 cm depth increment than the average value for 0–15 cm depth. As with total-P (Table 2) these difference are most pronounced for

Table 4 Values of total-P and Olsen-P based on NSI database (bulked 0–15 cm) for the four different soil types examined and also for all soils under arable and permanent grassland in England and Wales. Values relate to the national database except for the values specific to the Hampshire Avon (based on NSI sites within this catchment).

Soil type	Land use	N	Total-P (mg kg^{-1})	Olsen-P(mg l^{-1})†
Brown rendzina (3.43)	Arable	115	1157 (1054)‡	30 (23)
	Grassland	18	1476 (1238)	33 (15)
	All	168	1184 (1078)	28 (21)
Humic rendzina (3.41)	Arable	3	1397 (1479)	40 (35)
	Grassland	9	1453 (1548)	18 (11)
	All	20	1480 (1456)	23 (15)
Typical brown calcareous earth (5.11)	Arable	130	1027 (942)	33 (26)
	Grassland	33	1130 (1110)	21 (15)
	All	205	1077 (1023)	31 (24)
Typical argillic brown earth (5.71)	Arable	101	768 (680)	37 (30)
	Grassland	56	812 (753)	24 (14)
	All	255	767 (680)	33 (24)
All—Hampshire Avon	Arable	23	1236 (1237)	25 (20)
All—Hampshire Avon	Grassland	18	1343 (1388)	19 (15)
All—England and Wales	Arable	1888	830 (734)	32 (26)
All—England and Wales	Grassland	1560	939 (847)	24 (17)

†It is assumed that mg l^{-1} approximately equates to mg kg^{-1} for this database.
‡Values are means with medians in brackets.

the two grassland profiles, where surface values of Olsen-P are 19 and 39 mg kg^{-1} greater than average values for the 0–15 cm depth, for the Knoyle Down and Mere Down sites, respectively. For the soils under arable, surface concentrations of Olsen-P are between 3 and 25 mg kg^{-1} greater than average values for 0–15 cm depth.

It is useful to compare the values described above with values based on the NSI data set for the four soil types examined (Table 4). Table 4 illustrates the type of data that is commonly used in models to determine the extent and spatial variation of P transfers within river systems. Typically, soil-P input values are classified either according to soil type (i.e. subgroup) or by land use (i.e. arable or grassland). It is clear that the surface (0–2 cm) concentrations of total-P (Table 2) and Olsen-P (Table 3) for the four soil types in the Hampshire Avon catchment are considerably greater than equivalent values for the same soils based on the full national NSI database, especially in the case of Olsen-P.

CONCLUSIONS

The depth profiles of total-P and Olsen-P clearly demonstrate that there are variations in soil-P concentrations with depth in uncultivated grassland soils, particularly in the case of Olsen-P. For soils under arable, values of total-P are broadly constant within the plough layer. Concentrations of Olsen-P, however, exhibit maximum values near the soil surface reflecting inputs of fertilizers and manures to the soil surface between consecutive ploughing events. For 11 out of 12 soil-P profiles, the concentrations of soil-P in the surface layer (0–2 cm) are greater (in one instance >100%) than the average concentration for the 0–15 cm depth. This has important implications for the use of soil-P data based on bulked 0–15 cm soil cores for modelling surface transfers of P in river systems.

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