The use of phosphorus as a tracer in erosion/sedimentation studies

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Abstract Thirteen undisturbed soil cores (0.65 and 1.10 m deep) were taken in a cultivated micro-drainage basin in the Loess Belt of central Belgium. The analysis of the phosphorus content of these soil samples (taken every 0.1 m in depth) clearly shows that there is a phosphorus (P)-enriched layer in sedimentation areas which extends well below the plough layer. The depth of this layer gives an indication of the amount of sedimentation which occurred since the use of chemical fertilisers. Erosion areas are characterized by a sharp drop in P content at the contact between the plough layer and the subsoil. The use of phosphorus as a tracer in soil erosion/sedimentation studies was therefore compared with the use of caesium-137 (^{137}Cs) inventories which is a common technique to measure erosion/sedimentation rates over several decades. The results of this comparison indicate that the phosphorus analysis is less accurate than the ^{137}Cs method, but the predicted patterns are similar.

INTRODUCTION

The rate at which erosion and deposition processes occur can be measured directly for short time periods, but such data are difficult to extrapolate to longer time spans due to the spatial and temporal variability of the processes. To examine soil erosion over a longer period, tracers can be used. The most widely used tracer is ^{137}Cs, which allows assessment of soil distribution rates on arable land over the last 35 years. Disadvantages of the ^{137}Cs method are that the analyses are rather costly and require specialized equipment.

Phosphorus is strongly adsorbed onto soil particles. Measurements of suspended sediment samples at the outlet of two agricultural drainage basins situated in central Belgium clearly illustrate this (Steegen *et al.*, 1998). Therefore, one may expect that the sediment that is deposited within the catchment increases the soil P content at that place. Consequently, variations in soil P content are expected to be related to topography and could potentially be used to assess soil redistribution rates.

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The objectives of this study are to make a comparison of the P and ^{137}Cs inventories and to examine whether P inventories and profiles can be used in soil erosion/sedimentation studies.

METHOD AND MATERIALS

The study area is situated in the Loess Belt of central Belgium, near the village of Huldenberg between Brussels and Leuven. This area is rather vulnerable to water and tillage erosion, with average soil losses ranging between 1 and 100 t ha^{-1} $year^{-1}$ (e.g. Govers, 1991; Vandaele & Poesen, 1995). The micro-drainage basin that was studied is situated in one parcel and has a surface area of about 1 ha. The soils in this area are loess derived luvisols (<15% clay and <15% sand). In 1998, thirteen soil profiles located in this micro-basin were sampled along two transects crossing a small thalweg (pits 1–6 and 11–7) and one transect in the thalweg (pits 4, 9, 12 and 13). Figure 1 shows a map indicating the location of the P profiles in the landscape. For this micro-basin, data on ^{137}Cs content variations were already available (Quine *et al.*, 1994).

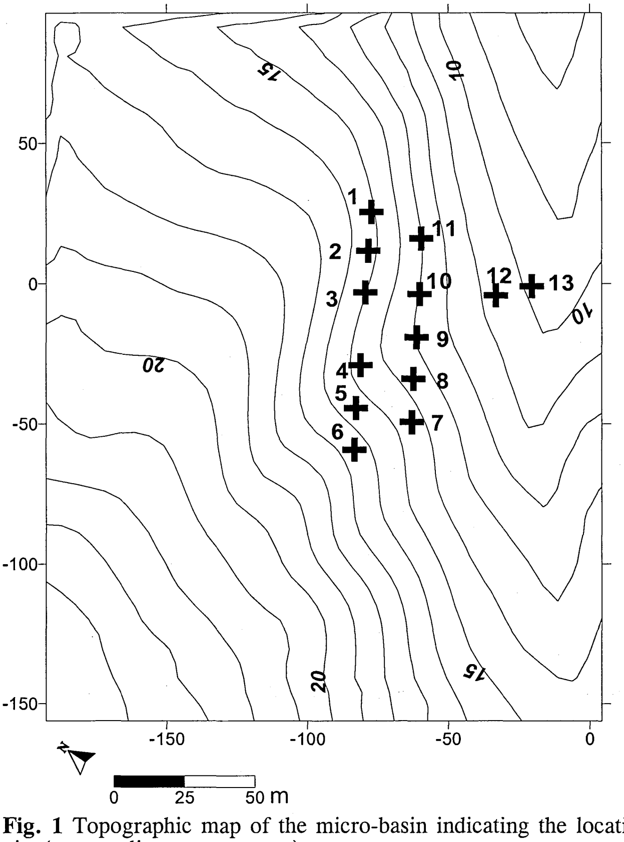

Fig. 1 Topographic map of the micro-basin indicating the location of the P profile pits (contour lines every metre).

The samples were taken using a drillhammer and the depth of the samples varied with their location in the landscape. On the convexities, samples were 0.6 m deep, while in the thalweg, samples were up to 1.4 m deep. The diameter of the sample core was 0.078 m. The compaction of the samples ranged between 0.7 and 9.2%. In general, a sample was taken every 0.05 m, but an additional sample was collected at the contact point between two different soil layers. In most cases, the samples taken every 0.01 m were analysed, but some additional samples were analysed as well. From the samples, the total P content was determined using the ignition method described by Takken & Verstraten (1996). Also, variations in grain size distribution within one profile were examined but were in general not important.

When the P profiles are to be interpreted in terms of sedimentation rates, one has to obtain data on P fertilization in the study area. Table 1 shows the trend of phosphorus use in Belgium from 1910 onwards and Fig. 2 shows the equivalent trend for the production of P fertilizers. From these two sets of figures, one may conclude that production of P fertilizers had already started at the end of the nineteenth century, but one can expect that fertilizer use started between 1900 and 1920, with the highest application around 1979. The exact starting date of P application is not known for this parcel, but it was already cultivated at the beginning of the twentieth century (Vandaele, 1997). The erosion and sedimentation rates obtained from the P profiles are therefore representative for a time period of 80–100 years.

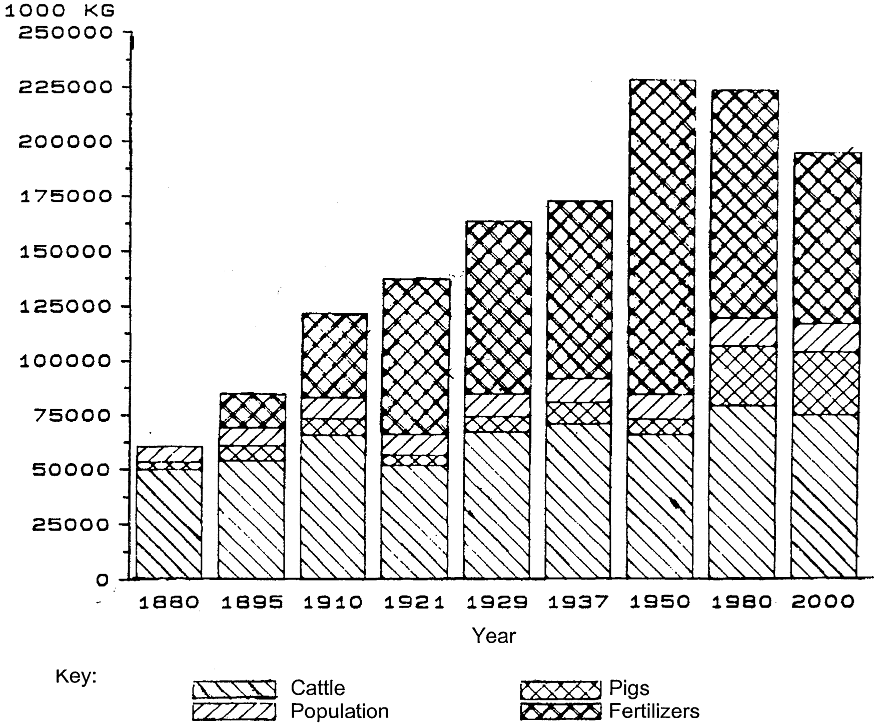

Fig. 2 Trend in the production of P fertilizers (P_2O_5) in Belgium (R. Tijskens (Boerenbond), personal communication).

Table 1 Trend of fertilizer use (kg ha^{-1} cultivated area) in Belgium (Hofman & Verloo, 1989).

Year	P_2O_5 (kg ha^{-1})
1910	20
1919	37
1940–1941	24
1950–1951	44
1960–1961	53
1970–1971	91
1980–1981	71
1983–1984	77

RESULTS

Considerable variations in soil P content with depth were measured. Phosphorus contents of the soil samples ranged between *c.* 200 and 1150 mg kg^{-1}, with the highest values measured in the topsoil. Figure 3(a) shows a typical P profile as observed on the convexities. At this location in the landscape, a sharp decrease in P content exists between the plough layer and the underlying soil. The toplayer (upper 0.25 m) is completely homogenized. Figure 3(b) is a soil profile taken on the slopes between the convexities and the thalweg. The P-enriched layer at this location extends some centimetres below the ploughed layer. Finally, Fig. 3(c) represents a profile taken in the thalweg. The soil layer that is enriched in P is much thicker here than in the other two locations. Moreover, there is not a sudden drop in P content,

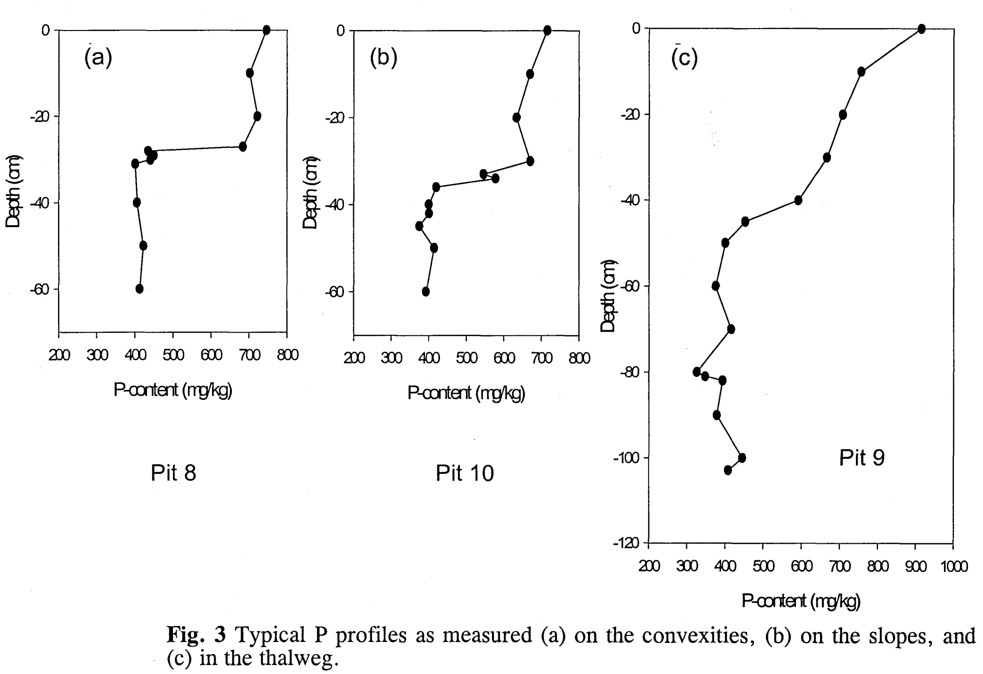

Fig. 3 Typical P profiles as measured (a) on the convexities, (b) on the slopes, and (c) in the thalweg.

Table 2 Location of the contact between P-enriched layer and subsoil (C: convexity, S: slope, T: thalweg).

Pit	Location	Thickness of P-rich layer (cm)	Compaction (%)	Corrected thickness of P-rich layer (cm)
1	C	–25	9.2	–27.3
2	C	–30	6.1	–31.8
3	S	–45	6.1	–47.7
4	T	–45	2.8	–46.2
5	S	–36	3.8	–37.4
6	C	–24	7.5	–25.8
7	C	–30	3.7	–31.1
8	S	–28	6.1	–29.7
9	T	–50	1.9	–50.9
10	S	–36	6.1	–38.2
11	C	–30	6.8	–32.0
12	T	–40	1.4	–40.6
13	T	–65	0.7	–65.5

but a rather smooth one. The results for the down-core change in P content are represented in Table 2 for each of the 13 pits.

The observed P pattern corresponds with what one expects, assuming that tillage operations have a major influence on the soil redistribution within the field, namely a thick P-rich layer in the thalweg due to sedimentation and a thin P-rich layer on the convexities due to erosion. Indeed, tillage erosion leads to high erosion rates on the convexities (e.g. Govers *et al.*, 1994). This will result in a sharp discontinuity between the P-enriched topsoil and the subsoil. In the thalweg, the eroded material is deposited and a gradual increase of the P content with depth is observed. The slopes between the convexities and the thalweg will have intermediate conditions. This was already concluded by Quine *et al.* (1994), who found that the incisions by water occurred only episodically in the thalweg, and that these incisions were compensated by valley-infilling as a result of tillage operations.

Thus, there is a qualitative agreement between the ^{137}Cs and P methods. To evaluate whether the P profiles can predict the absolute amounts and rates of sedimentation, our data are compared with the ^{137}Cs measurements reported by Quine *et al.* (1994) on samples from the same field. The locations of the sampling points from which ^{137}Cs was determined in the study of Quine *et al.* do not correspond with locations of the sampling points for P analysis. However, an overlay of the location of the P profiles, measured using GPS with the interpolated map of ^{137}Cs inventories, allowed to estimate the ^{137}Cs inventory at the locations where the P profiles were taken.

COMPARISON WITH THE CAESIUM-137 METHOD

Samples for ^{137}Cs analysis were taken to a depth of 0.6 m. The ^{137}Cs inventory of these samples was expressed as the total content of the whole sample divided by unit surface area (Bq m^{-2}). Therefore, the total P content of each profile up to the depth at which the background level was found was calculated and divided by the unit surface area. First, a linear interpolation between the P contents of the measured points was made for each centimetre and then this value was multiplied by the bulk density of the material (1300 kg m^{-1}) and the volume of the sample and divided by the unit surface area. The value is expressed in g P m^{-2}. Figure 4 shows the two inventories plotted against each other. From this graph it is obvious that the P and ^{137}Cs inventories are strongly correlated and vary in a similar way over the landscape (r^2 = 0.699). However, it should be clear that these inventories are not totally equivalent. The variations in ^{137}Cs result from the redistribution over several decades of a tracer that was applied in a relatively short period. On the other hand, P has been applied continuously to the soil in relatively large quantities over almost a century.

Based on the depth at which the background P level was found and, taking into account a 0.25 m deep plough layer, deposition rates were calculated for the four profile pits in the thalweg (pits 4, 9, 12, 13) (Table 3). The average sedimentation rate for the four pits ranged between 2.5 and 3.2 mm $year^{-1}$, depending on the time-interval since the start of P fertilization (100 and 80 years respectively). Using the optimal model to simulate erosion and sedimentation rates based on ^{137}Cs data and, taking into account tillage and water erosion, the sedimentation rate for the four pits in the thalweg of the study area, equals 2.5 mm $year^{-1}$ (measured over a period of 38 years, Table 4). Thus, the absolute sedimentation rates obtained from the P and the ^{137}Cs methods have the same order of magnitude.

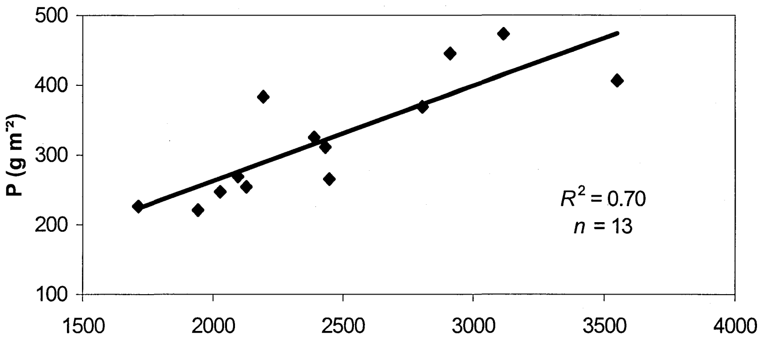

Fig. 4 A plot of P inventories against ^{137}Cs inventories. The regression is significant at the 95% level of confidence.

Table 3 Calculation of sedimentation rates using P as a tracer.

Pit	Corrected thickness of P-rich layer (cm)	Thickness of deposited layer (cm)	Rate of sedimentation (mm $year^{-1}$): 80 years	100 years
4	-46.2	21.2	2.65	2.12
9	-50.9	25.9	3.24	2.59
12	-40.6	15.6	1.95	1.56
13	-65.5	40.5	5.06	4.05
Average:			3.23	2.58

Table 4 Sedimentation rates calculated for the four pits in the thalweg based on ^{137}Cs inventories (over 38 years).

Pit	Accumulation (m)	Sedimentation rate (mm $year^{-1}$)
4	0.112	2.94
9	0.070	1.85
12	0.078	2.05
13	0.129	3.40
Average		2.56

Our data indicate that P can be used as a tracer in sedimentation studies. However, there remain some uncertainties with respect to both spatial and temporal variations in P application, P uptake by plants and to variations in plough depth.

The lack of a reference site for P as used in ^{137}Cs studies is a disadvantage and prohibits estimation of absolute erosion rates. Indeed, ^{137}Cs is deposited on the soil surface at a spatially uniform rate, whereas P is added as a fertilizer on cultivated fields and not on parcels under pasture. A reference site under pasture (where no erosion is observed) can therefore not be established and a reference site on the cultivated field is always disturbed as tillage operations displace material. This implies that P can be used to detect spatial variations in erosion and sedimentation, but the determination of absolute erosion rates is difficult. On the other hand, the determination of the P content of a soil sample is relatively rapid and cheap, so that detailed information on P enrichment with depth can be obtained. This allows a relatively accurate determination of sedimentation rates, provided that data are available on the onset of P application.

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