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The sediment budgets of cultivated slopes and slope catchments: an evaluation of the influence of slope morphology

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Abstract Evaluation of the net soil losses from cultivated slopes represents an important requirement for assessing sediment redistribution in river basins. Different methods can be used to determine the spatial pattern of soil loss/deposition within cultivated areas. These include the soil-morphological method, direct measurement of rills and deposition zones and radionuclide techniques. The soil-morphological method provides information on soil losses for the entire period of cultivation. Soil losses for single erosion events can be assessed using direct measurements of rills. The caesium-137 (^{137}Cs) and excess lead-210 ($^{210}Pb_{ex}$) techniques provide information on sediment redistribution over approximately the past 50 and 100 years respectively. Available data concerning net soil losses from slopes of different topographic configurations, obtained using these different methods, were collected from studies undertaken in various landscape zones around the world. The relationship between erosion and deposition was shown to be very similar for slopes or slope catchments of similar configuration, despite differences in the temporal scales, the methods employed and the landscape characteristics (soil, precipitation, etc.). Hence, the morphological characteristics exert a key influence on sediment redistribution on hillslopes. Establishment of buffering capacity coefficients for different slope types permits the sediment output from cultivated areas to be predicted, based on a classification of slope morphology and using information from topographic maps or DEMs.

Key words deposition; sediment redistribution; slope form; slope sediment budget; soil erosion

INTRODUCTION

Direct observations of water flow and sediment transport on cultivated slopes demonstrate that processes of erosion and deposition interact along the slope immediately after the first soil particles are mobilized. Different landscape characteristics influence the relationship between particle detachment, transport and deposition. For example, Walling & Quine (1991) showed that soil grain size exerts an important influence on sediment redistribution on cultivated slopes in Great Britain (Fig. 1). Similar relationships between soil type and sediment transfer on cultivated slopes were reported for southwestern Saskatchewan (Pennock *et al.*, 1995). However, the topography of cultivated slopes is the key parameter controlling sediment redistribution, because it determines the overland flow energy (Zaslavsky & Sinai, 1981).

Arable land usually occupies slopes of varying length with gradients in the range 0–15°. The slope profile and plan curvature determine the dominant direction of flow, and hence exert a major impact on soil redistribution within cultivated fields. Different

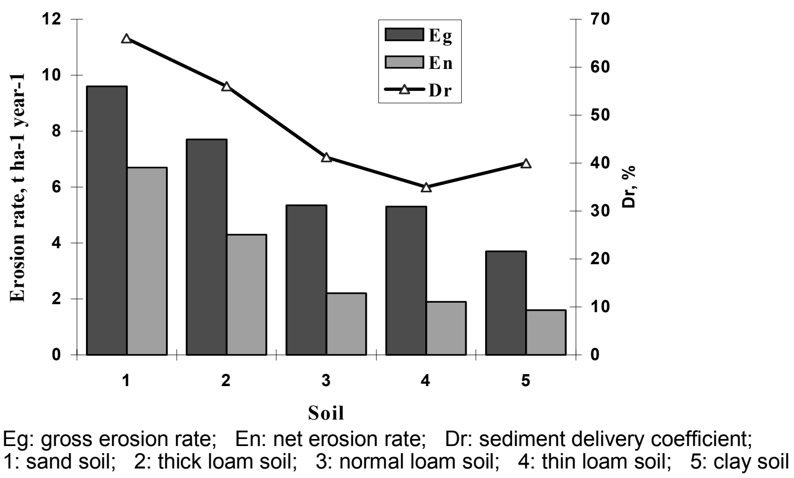


Fig. 1 Erosion rates and sediment delivery coefficients for soils of different grain size in Great Britain (based on data from Walling & Quine, 1991).

landform classifications have been developed to divide the landscape into morphological elements with distinctive hydrological regimes (e.g. Lopyrev, 1977; Pennock *et al.*, 1987). A range of different methods is currently available for evaluating sediment redistribution on slopes. Direct measurement of rill networks, the soil-morphological method and the ^{137}Cs technique are the most widely used. The objective of this paper is to suggest a morphological classification for slopes, based on the relief energy, which may be used for evaluation of sediment redistribution, and to evaluate available quantitative data regarding sediment redistribution on slopes and within slope catchments of different configuration.

A MORPHO-ENERGETIC CLASSIFICATION OF SLOPES

Recent advances in the creation of digital elevation models (DEMs) permit detailed representation of the topography of study slopes or slope catchments. DEM resolution will vary and increasing coarseness tends to cause a decrease in mean slope and an increase in catchment area (Wolock & McCabe, 2000). The availability of a DEM facilitates the identification and delineation of slopes and slope catchments of different configuration. Appropriate morphological classifications of agricultural slopes should be used to distinguish slopes of different shape or with different systems of elementary slopes (SES) (Litvin, 2002) (Fig. 2). The physical basis of classification should reflect the change in the vertical component of gravitational force, which is the main factor controlling the transformation of the potential energy of water to kinetic energy. The main components of such a classification are the possible combinations of elementary slopes.

The classification should include all possible three-dimensional slope configurations (Fig. 3), which control overland flow direction and changes in flow depth. Parallel slopes are characterized by the absence of plan curvature. Arc slopes are represented on topographic maps by straight non-parallel horizontal lines. Various types of radial slope are the most widespread in nature. Each type of SES within a study basin will be

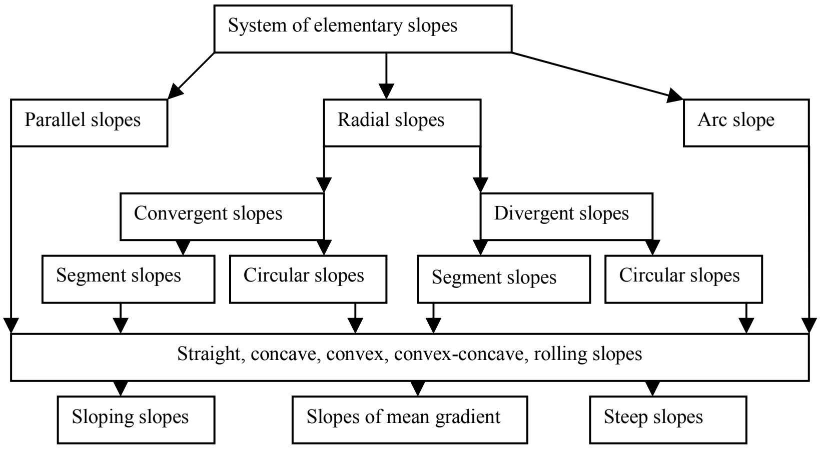
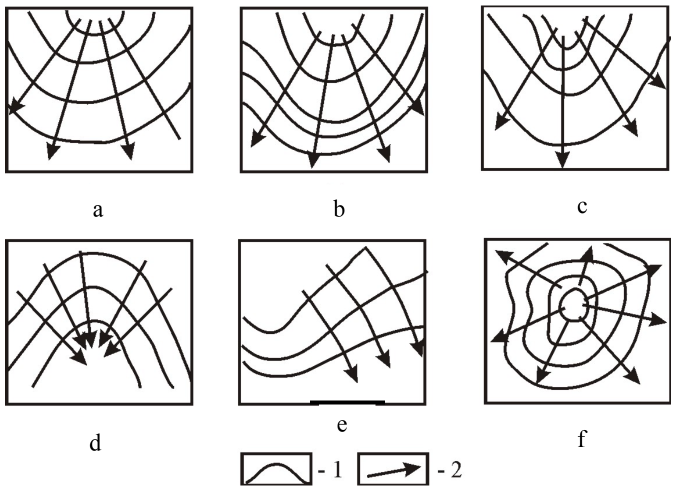


Fig. 2 Morphological classification of slopes.



a: radial divergent segment straight SES; **b**: radial divergent segment convex SES; **c**: radial divergent circular convex SES; **d**: radial convergent concave SES; **e**: arc straight SES; **f**: radial divergent circular straight SES; **1**: horizontal; **2**: flow line.

Fig. 3 Examples of different systems of elementary slopes (SES) as depicted on topographic maps.

characterized by a specific sediment delivery coefficient or connectivity ratio (Walling *et al.*, 2004). It should therefore be possible to calculate the sediment transfer from the slopes of a catchment to the adjacent uncultivated parts of the slope or to the river valley, based on the known area of each SES determined from the DEM and information on the connectivity ratios associated with of particular types of SES. The suggested classification does not include linear elements of slope relief (i.e. hollows or gullies), because they are treated as first order elements of the drainage network.

EVALUATION OF SEDIMENT REDISTRIBUTION ON CULTIVATED SLOPES

Sediment redistribution on cultivated slopes depends on a number of different factors, including, direction and depth of tillage, magnitude and frequency of erosion events, crop rotation, etc. Extreme erosion events will exert a stronger influence on sediment transfer than lower magnitude, more ordinary, events. For example, Edwards & Owens (1991) reported that three rainstorm events were responsible for more than 50% of the total soil loss from nine slope catchments during a 30-year period of observation. Similarly, Chernyshev (1969) reported that 60% of the total soil loss from eleven catchments in the Kiev region during the period 1959–1966 occurred during three storm events. Assessments of sediment redistribution for a study slope derived for different time intervals using different methods may therefore differ.

Combination of direct measurements of water and sediment discharge at the outlets of cultivated slope catchments with measurements of rill network volumes and the volume of sediment deposits within the catchments, permit the inter-annual variability of the difference between gross and net erosion to be assessed (Table 1). The slope micro-relief, which primarily reflects the direction, type and depth of cultivation, exerts an important influence on sediment redistribution on cultivated slopes with gradients in the range 1–6°. Similar observations were made during a 12-year period for slope catchments within the Middle Russian Upland with a dominance of convex slopes. Annual gross erosion averaged 15.4 t ha year^{-1}, with redeposition within the cultivated slopes accounting for about 65% of the mobilized sediment (Braude, 1991). It is interesting to note that about 30% of the deposition on the slopes was associated with filtration of overland flow through snow, because of the irregularity of the snow cover. Differences in slope gradient exert an important influence on deposition rates within similar landscapes. For example, Eschenko (1982) reported that up to 90% of the mobilized sediment was deposited within cultivated fields with a 1–2° gradient within the Pridneprovie lowland, whereas only 5–15% of the mobilized sediment was detained on steeper slopes. According to Kolesnikov & Belolipski (1989), between 15 and 45% of the mobilized sediment is deposited within the cultivated convex slopes of moderate gradient small catchments in the Doneck Uplands. Detailed measurements of sediment redistribution undertaken over a period of approximately one decade on convexo-concave slopes (gradient 1–11°) within the Podol'skaya upland (western Ukraine) by Koval'chuk (1995) showed that deposition was highly variable from year to year, with values ranging from 19 to 71% during snow-melt and between 23 and 67% for rainstorms. However most of the sediment was deposited on the footslopes of concave slopes.

Mean annual values of the percentage of sediment mobilized by gross erosion that is deposited, derived from direct measurements of rill network volume and the volume of depositional bodies, undertaken simultaneously with measurements of water and sediment discharge, are summarized in Table 2. The results of sediment deposition measurements undertaken after single erosion events are not considered because of their high variability.

The application of different variants of the soil-morphological approach for evaluating sediment redistribution is relatively uncommon for several reasons. Firstly, this approach is traditionally used primarily for establishing the extent of areas with different levels of soil loss. Secondly, the soil-morphological method is based on estimates of the change in soil horizon thickness over the entire period of cultivation, which can vary from a few decades (e.g. some areas of the Russian steppe zone) to thousands of years (e.g. China, Western Europe, etc.). It is often very difficult to establish the precise duration of cultivation for a study field. However, the duration influences the erosion rate estimate. This problem is of less importance for most of the steppe and

Table 1 The relationship between erosion and deposition within cultivated slope catchments in the Protva River basin.

Catchment number	Year	Gross erosion (t)	Net erosion (t)	Deposition within field (t)	Deposition as a % of gross erosion
1	1982	25.2	20.4	4.8	19
1	1983	106.4	97.6	9.8	9
1	1984	13.8	4.2	9.6	70
1	1985	62.3	49.7	12.6	20
2	1983	3.4	3.4	0	0
2	1985	0.26	0.26	0	0
3	1983	0.32	0.32	0	0
3	1984	7.6	2.0	5.6	74
4	1983	0.9	0.9	0	0
4	1984	4.35	2.35	2.0	46

Table 2 Sediment deposition (% of gross erosion) within cultivated slopes and slope catchments of different configuration, established using different methods.

Slope configuration of cultivated area	Rill/cone net measurements	^{137}Cs technique	Soil morphological method	Mean value
Hollow catchment, sloping convex slopes	34–39	40–45	25–63	41
Hollow catchment, steep convex slopes	–	20–40	10–20	22.5
Concave slopes	50–60	75–85	–	68
Straight slopes	35–45	25–65	10–16	29
Steep convex slopes	7–12	15–25	10-12	13.5
Convex slopes of mean gradient	15–45	40–50	–	(35)
Sloping convex slopes or with tillage dam at the footslope	55–70	70–80	–	69
Mean value	39	48	–	39

forest-steppe zones of Russia and Canada and the prairies of the USA, where intensive cultivation began about 250–300 years ago. It is well-known that the incidence of slope cultivation is closely connected with the availability of ploughs and related implements. One method for determining the length of the period of cultivation for a given slope developed by Dobrovol'skaya & Larionov (1999) is based on the relationship between implement requirements and availability, and slope gradient.

Only a few attempts have been made to determine soil loss/gain using the soil-morphological method (Pennock & de Jong, 1987; Ivanov & Nazarenko, 1998). Usually information on the spatial extent of areas of eroded soil and soil deposition are the key outputs reported in publications presenting the results of the application of this approach. Kashtanov & Zaslavski (1984) conclude on the basis of an analysis of publications dealing with areas of eroded and deposited soil on cultivated land in different regions of the USSR, that deposited soil commonly occupies ~30% of the total area of arable land. It is possible to suggest that the mean deposition rate, calculated on the basis of the area of deposition within a cultivated field, is likely to equal or even exceed the mean erosion rate, calculated relative to areas of eroded plus stable soil. A minimum of 30% of the eroded sediment was found to be redeposited within cultivated fields.

The most detailed information on patterns of soil redistribution is provided by the ^{137}Cs technique, which has become widely used during the last decade (Walling *et al.*, 1996). In common with the soil morphological method, the ^{137}Cs technique allows the total soil redistribution associated with water, wind and tillage erosion to be established. It has been shown that 20–23% of the eroded sediment was deposited within the cultivated parts of hollow catchments with steep slopes (5–7°) (Walling *et al.*, 1996, 1998). Maximum deposition is generally in the bottom of the hollows, close to the footslopes, and this can probably be explained by the influence of tillage erosion. Hollow catchments with slopes of 1–2° are characterized by high rates of sediment deposition in the hollow bottoms (Walling *et al.*, 1986; Bernard *et al.*, 1998). Only 50–60% of the mobilized sediment is exported from the cultivated part of such catchments.

Relatively straight convergent slopes are characterized by a predominance of erosion within the upper and middle parts of the slope and deposition on the footslopes. The proportion of the mobilized sediment that is deposited within the slopes of a given configuration decreases with increasing slope gradient from approx. 60–65% (e.g. Walling & Quine, 1992) for relatively gentle slopes, to 20–22% for steep slopes (e.g. Walling *et al.*, 2000). Steep convex slopes dissected by very small hollows are characterized by a dominance of erosion (about 80%) over deposition (about 20%) (Higgitt, 1995; Schuller *et al.*, 2003). However, where artificial buffer strips or tillage dams are found at the bottom of the slope, about 50% of the sediment can be deposited there (Owens *et al.*, 1997). About 80% of the mobilized sediment is deposited on the bottom third of concave slopes (Laverdiere & Bernard, 1998). Available data concerning sediment redistribution provided by the ^{137}Cs technique are summarized in Table 2.

Available data concerning sediment redistribution on cultivated slopes demonstrate that, despite the different time scales associated with different methods, the values of deposition associated with slopes or slope catchments of a given configuration are relatively similar (Table 2). The data presented in Table 2 were derived for different landscape zones of the world, but there are no major differences between the values reported for slopes of similar type. This confirms the primary role of landform configuration in controlling sediment redistribution.

CONCLUSIONS AND PERSPECTIVES

There is a strong need to improve our understanding and prediction of sediment redistribution on cultivated slopes because eroded sediment is a key contributor to problems of soil degradation, surface water pollution and reservoir siltation. However, documentation of sediment redistribution within cultivated areas characterized by different slope morphological configuration is a costly exercise. Different approaches are required. One promising approach involves the use of DEMs or topographic maps to subdivide cultivated slopes according to a morphological classification and the designation of sediment delivery ratio coefficients for each slope type. The preliminary analysis of published data concerning sediment redistribution on cultivated slopes presented above demonstrates that relatively similar values are associated with particular slope or slope catchment types, irrespective of the different methods employed and different landscape zones involved. This confirms the primary role of slope morphology in controlling sediment redistribution. However, the available quantitative data concerning sediment redistribution unfortunately do not currently provide a complete coverage of all possible types of SES. Improvement of existing procedures for classifying slope morphology and collection of further field data to provide information concerning deposition rates within SES of different types should be seen as important research needs.

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