

## **A comparison of the roles of tillage and water erosion in landform development and sediment export on agricultural land near Leuven, Belgium**

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**Abstract** There is growing evidence that tillage processes may be important influences on the pattern of soil redistribution and landform development. This study uses evidence from caesium-137 ( $^{137}\text{Cs}$ ) measurements, observation of water erosion, and mathematical simulation of tillage, to investigate the roles of water erosion and tillage in determining long-term patterns of soil redistribution, sediment export and landform modification for a field on loess soils near Leuven, Belgium. The pattern of long-term soil redistribution, represented by the distribution of  $^{137}\text{Cs}$ , is largely controlled by tillage displacement. Sediment export is dominated by water erosion with 60% of the exported sediment derived from a valley floor thalweg occupying only 7.5% of the study area and 39% from slope concavities occupying 15.5% of the area. Despite the incision effected by episodic water erosion, landform development in this field is dominated by valley-infilling as a result of annual tillage operations.

### **INTRODUCTION**

As a result of the often dramatic evidence of rilling and gullyng on agricultural land in western Europe (cf. Evans & Nortcliff, 1978; Poesen, 1993), increasing attention has been directed to the role of medium to high magnitude low-frequency fluvial erosion events in determining patterns of soil erosion and landform development. However, recent studies of longer-term soil redistribution within agricultural fields, undertaken using the caesium-137 ( $^{137}\text{Cs}$ ) technique, have produced data which point to the importance of processes other than fluvial erosion. Quine & Walling (1993) examined the relationship between a range of topographic parameters and  $^{137}\text{Cs}$ -derived erosion rates, from fields on a range of soil textures in the UK, and found that the highest correlations were between erosion rate and profile or planform curvature at four of the five sites. These results were not consistent with the dominance of water erosion, as this would be expected to be influenced primarily by slope angle and upslope length or area. (Only one of the five sites showed a statistically significant correlation at the 95% level

between slope angle and erosion rate, and only one site showed a significant correlation between upslope area and erosion rate). Furthermore, an investigation of long-term soil redistribution rates along two slope profiles, based on both  $^{137}\text{Cs}$  data and topographic observations at the field boundaries, suggested that tillage processes were as important as water erosion in determining the long-term pattern of soil redistribution (Govers *et al.*, 1993). This latter interpretation is consistent with a growing body of experimental data which has demonstrated the potential for tillage to displace significant masses of soil with each operation (Lindstrom *et al.*, 1990, 1992; Govers *et al.*, 1994). The study described here uses measurements of  $^{137}\text{Cs}$  redistribution, observations of water erosion, and simulation of tillage to examine the influence of both water erosion and tillage in determining long-term spatial patterns of soil redistribution within an agricultural field near Leuven, Belgium. The resultant data are evaluated with regard to the relative importance of lower-magnitude, high-frequency tillage and potentially high-magnitude, low-frequency water erosion in determining landform development and sediment export.

## THE HULDENBERG SITE

The field selected for investigation ( $4^{\circ}35'E$ ,  $50^{\circ}49'N$ ) lies in the loess belt of central Belgium near the village of Huldenberg, between Brussels and Leuven. The soils of this area are very susceptible to soil erosion by water (Govers, 1991; Poesen & Govers, 1990; Poesen, 1993; Vandaele, 1993) and the rolling topography of the area may be expected to lead to significant spatial variation in net soil loss and gain by tillage displacement (Lindstrom *et al.*, 1992).

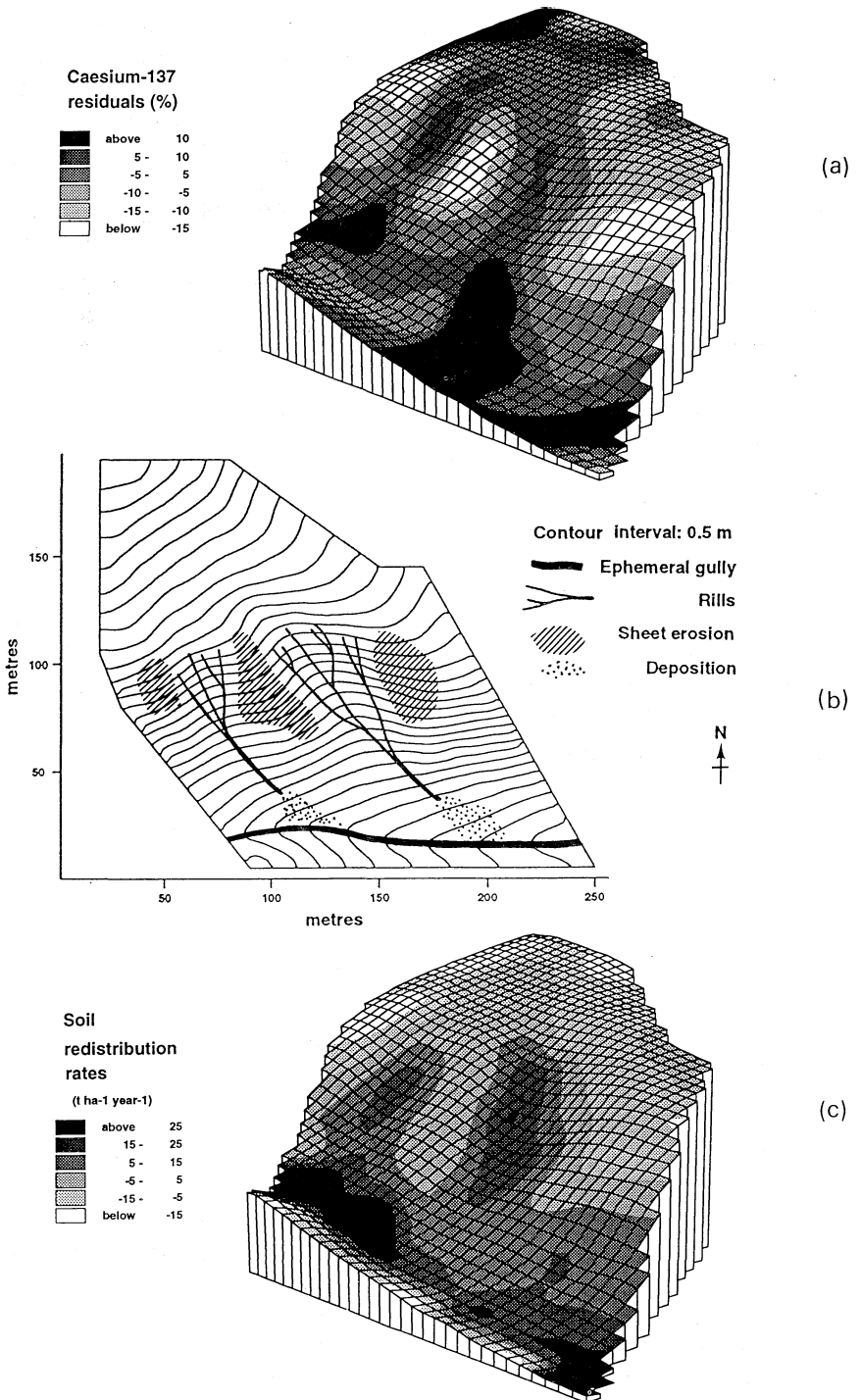
## DATA SOURCES

### Caesium-137 data

The caesium-137 technique is now well-established and has been described in full elsewhere (cf. Walling & Quine, 1991). Detailed discussion of the basis of the technique is beyond the scope of this paper. In short,  $^{137}\text{Cs}$  inventories (activities per unit area) measured at the study site are compared to an estimate of the atmospheric input obtained at a "reference site". Areas within the field which evidence  $^{137}\text{Cs}$  loss are identified as eroding, and estimates of erosion and deposition rates are derived from the magnitude of  $^{137}\text{Cs}$  loss or gain, respectively.

Soil samples for  $^{137}\text{Cs}$  analysis were collected from the study field and an adjacent area of uncultivated, level grassland (the reference site), using core tubes of 7.5 cm and 11 cm diameter. The samples were air-dried, lightly ground and sieved, and a sub-sample of the  $\leq 2$  mm fraction was analysed for  $^{137}\text{Cs}$  by gamma spectrometry in the Radionuclide Laboratory of the Department of Geography at the University of Exeter. Count times were typically c. 28 000 s, providing a measurement precision of c.  $\pm 4\%$ .

The  $^{137}\text{Cs}$  inventories from the area of uncultivated grassland were used to provide an estimate of the local reference inventory ( $250 \pm 9 \text{ Mbq cm}^{-2}$ ). This value was used to calculate the percentage loss or gain of  $^{137}\text{Cs}$  ( $^{137}\text{Cs}$  percentage residuals) from each of the 106 sampling locations in the study field. The percentage residuals have been used to plot the spatial pattern of  $^{137}\text{Cs}$  redistribution which is shown in Fig. 1(a). This



**Fig. 1** The study field at Huldberg: (a) measured <sup>137</sup>Cs residuals (%) superimposed upon an isometric projection of the field topography; (b) a typical pattern of rilling, gullying and sediment deposition as a result of water erosion; (c) simulated distribution of soil redistribution as a result of tillage.

pattern shows clear topographic control with maximum  $^{137}\text{Cs}$  loss from the slope convexities, and evidence of  $^{137}\text{Cs}$  gain in both the slope concavities and along much of the main thalweg. The area of  $^{137}\text{Cs}$  gain at the upper margin of the sampled area is probably the result of soil influx from the adjacent field.

### Topographic data

All sampling locations were recorded and a detailed topographic survey of the study field was undertaken using a total station (incorporating an electronic theodolite and EDM). The resultant topographic data, with a resolution of ca 450 points per hectare, were used with the SAS G3GRID procedure (SAS Institute, 1990) to build a Digital Elevation Model (DEM) of the field with a grid size of 2.5 m. This DEM was used for all model simulations.

### Observation of water erosion

The field sampled in this study has been monitored for visible evidence of water erosion over a period of 4 years. After each period of potentially erosive precipitation the field was visited and all rills and gullies were surveyed. On the basis of this work it is possible to present a typical distribution of the rilling, gullying and sediment deposition by water for the field (Fig. 1(b)). Furthermore, it is possible to identify the magnitude of the erosion represented by these features. The ephemeral gully in the main thalweg is incised annually, causing erosion of 5 to 10 m<sup>3</sup> of sediment. In the zero-order slope concavities incision takes place approximately 1 year in 2, with erosion of 1.5 to 3 m<sup>3</sup> of sediment from the western concavity and 1.5 to 5 m<sup>3</sup> from the eastern concavity. However, it is not possible to quantify the amount of sediment redeposited in the depositional zones, nor the amount of soil eroded by sheet erosion from the spurs. Despite these limitations, the observations provide a valuable basis for comparison with the  $^{137}\text{Cs}$  distribution.

### Tillage simulation

Simulation of soil redistribution by tillage was based on investigations undertaken by members of the Catholic University of Leuven (Govers *et al.*, 1994) at the Huldenberg experimental field (within 1 km of the studied field) and on other published work (Lindstrom *et al.*, 1990, 1992). These data indicate that the sediment flux, due to tillage, through any point on the slope is proportional to the slope angle and the soil redistribution rate is, therefore, proportional to the rate of change of slope angle:

$$Q_t = kS$$

$$E_t = -\{(\delta Q_t/\delta x) + (\delta Q_t/\delta y)\}$$

where:  $Q_t$  = sediment flux due to tillage (kg m<sup>-1</sup>);  $S$  = tangent of slope angle;  $E_t$  = erosion due to tillage (kg m<sup>-2</sup>);  $x,y$  = distance from divide (m);  $k$  = constant (kg m<sup>-1</sup>).

In this study, the model was used to simulate the two-dimensional pattern of net soil redistribution due to tillage over a 38 year period (for comparison with  $^{137}\text{Cs}$  data). Two soil redistribution episodes were simulated for each year, one to represent ploughing and one to represent discing and seed-bed preparation. For each redistribution episode a value of  $275 \text{ kg m}^{-1}$  was used for the constant  $k$ . The resultant time-averaged data were used to estimate the mean annual tillage redistribution rates which are shown in Fig. 1(c). The predicted pattern reflects the diffusive nature of the tillage process, with maximum soil loss from the slope convexities and maximum gain in both the slope concavities and the main thalweg. The very clear contrasts between the predicted pattern for tillage and the observed distribution of water erosion suggest that a qualitative comparison of these distributions with the pattern of  $^{137}\text{Cs}$  residuals should provide an indication of the relative importance of the soil redistribution processes operating within the field.

### COMPARISON OF SPATIAL DISTRIBUTIONS

Visual comparison of the measured pattern of  $^{137}\text{Cs}$  residuals (Fig. 1(a)) with the patterns of soil redistribution observed for water erosion (Fig. 1(b)) and simulated for tillage (Fig. 1(c)) reveal a clear similarity with the tillage simulation and divergence from the observed pattern of water erosion. In particular, the positive  $^{137}\text{Cs}$  residuals in the slope concavities are mirrored by predicted tillage aggradation in these areas and the negative residuals on the spur convexities coincide with predicted tillage erosion. A more quantitative comparison can be obtained by plotting the measured  $^{137}\text{Cs}$  residuals against the predicted tillage redistribution rates (Fig. 2). All sample sites located on the

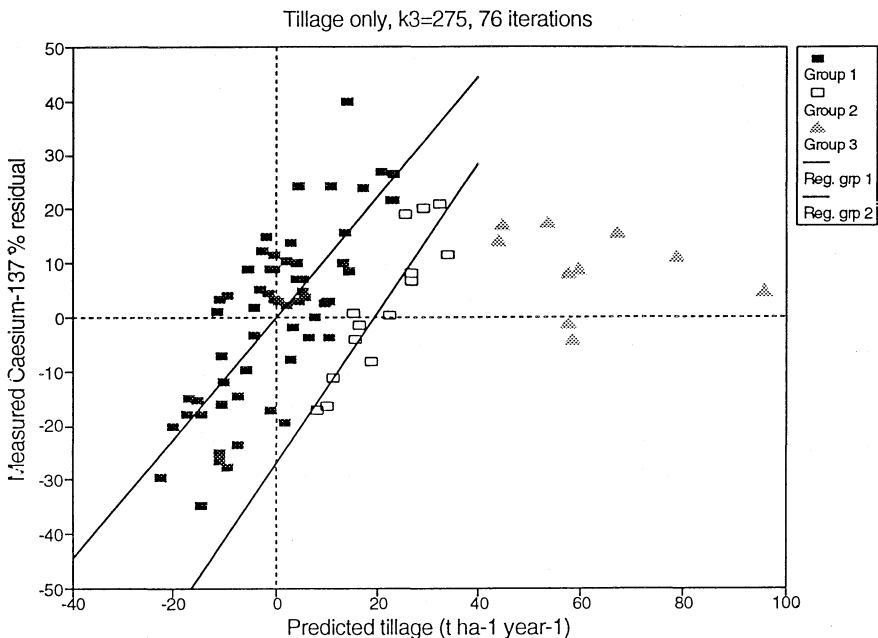


Fig. 2 The relationship between measured  $^{137}\text{Cs}$  residuals and predicted rates of soil redistribution by tillage.

boundaries have been excluded from the figure because of problems of simulation in the boundary zone and the uncertainty regarding potential sediment input from upslope cultivated areas. Visual inspection of Fig. 2 permits the subjective sub-division of the plotted points into three groups which are discussed individually.

As might be expected on the basis of Fig. 1, the majority of the plotted points evidence a positive relationship between the measured  $^{137}\text{Cs}$  residuals and the predicted tillage redistribution rates. In the case of group 1 (representing 71% of the samples) variation in predicted tillage redistribution rates accounts for 59% of the observed variation in  $^{137}\text{Cs}$  residuals and the regression line passes through the origin ( $^{137}\text{Cs}$  residual = predicted tillage rate \* 1.107). This suggests that over the majority of the area the redistribution processes are dominated by tillage.

Variation in predicted tillage redistribution rates also accounts for 82% of the observed variation in  $^{137}\text{Cs}$  residuals for group 2. However, the regression line for group 2 ( $^{137}\text{Cs}$  residual =  $-26.9 + \text{predicted tillage rate} * 1.385$ ) indicates that when tillage redistribution is zero, a  $^{137}\text{Cs}$  residual of  $-27\%$  is expected. This suggests that the locations represented by group 2 have been subject to loss of soil-associated  $^{137}\text{Cs}$  by processes other than tillage. Of the 14 sampling points in group 2, four are located in the western slope concavity, six in the eastern slope concavity, and two on the margin of the main thalweg. All of these locations coincide with the observed distribution of water erosion (Fig. 1(b)). Furthermore, the final two sample locations in group 2 lie on the steep slopes above the eastern end of the main thalweg. It, therefore, seems reasonable to attribute the increased loss of  $^{137}\text{Cs}$ , associated with group 2, to erosion by water.

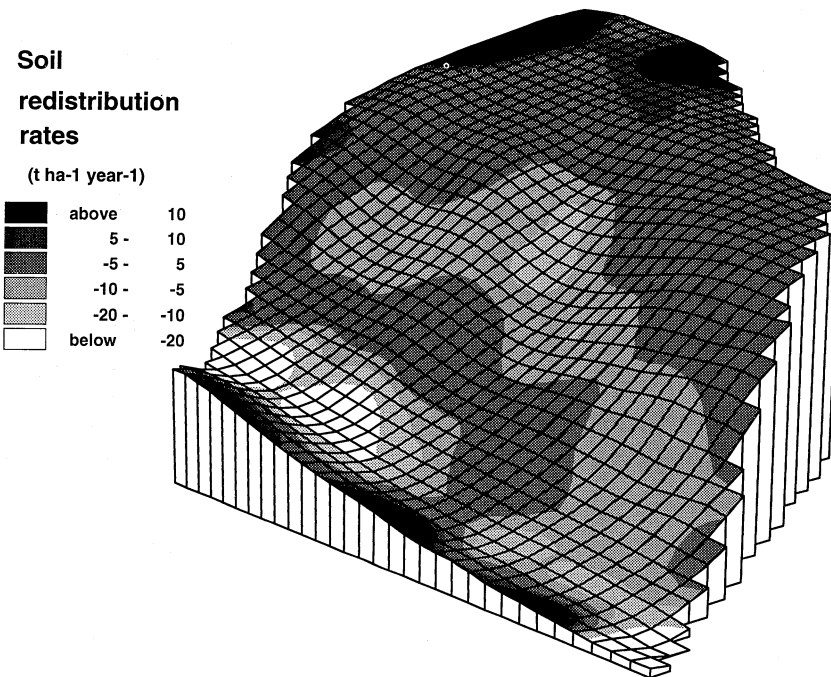
Group 3 shows clear deviation from the positive relationship between  $^{137}\text{Cs}$  residuals and tillage redistribution rates, with  $^{137}\text{Cs}$  residuals much lower than expected on the basis of the tillage simulation. However, this deviation may be explained by consideration of the topographic location of the sampling points included in this group. Three of the points lie at the base of the eastern zero-order slope concavity and the remaining eight represent all of the points lying along the line of the main thalweg. This distribution, which coincides with the field observations of the pattern of rilling and gullying (Fig. 1(b)), suggests that the significant deviation in  $^{137}\text{Cs}$  residuals from values which could be expected as a result of tillage may be attributed to the action of high rates of water erosion.

This comparison indicates that over most of the field the pattern of  $^{137}\text{Cs}$  redistribution may be largely attributed to the impact of tillage, but that at 29% of the non-boundary sample locations there is evidence of further significant  $^{137}\text{Cs}$  loss which may be attributed to water erosion.

## RATES OF WATER EROSION

In order to quantify the role of water erosion in the study field it is necessary to estimate the loss or gain of soil represented by the observed  $^{137}\text{Cs}$  residual, while taking into account  $^{137}\text{Cs}$  redistribution due to tillage displacement. In this study, this has been undertaken using a mass-balance model which simulates  $^{137}\text{Cs}$  fallout deposition (from both bomb-tests and Chernobyl), mixing, and soil-associated loss and gain in association with both water erosion and tillage displacement. For each sampling point, the predicted rate of soil redistribution by tillage was assumed to be correct and this was used in the

simulation with a range of water erosion and aggradation rates until agreement was found between the predicted and measured  $^{137}\text{Cs}$  residuals. It was, therefore, possible to estimate the rate of water erosion or deposition required at each sample location to produce the observed pattern of  $^{137}\text{Cs}$  residuals. The point estimates of water erosion derived using this procedure have been interpolated to show their spatial distribution (Fig. 3) which compares favourably with the pattern of observed water erosion (Fig. 1(b)). Furthermore, the  $^{137}\text{Cs}$ -derived estimates of water erosion provide an indication of the distribution and severity of sheet and inter-rill erosion which are not measurable in the field. These processes are indicated by the extensive zone with erosion rates in the range 5 to 10  $\text{t ha}^{-1} \text{ year}^{-1}$ . Much of this zone coincides with the area of sheet erosion observed in the field. However, there is an additional area of soil loss on the steep slopes adjacent to the eastern end of the main thalweg which may be attributed to sheet and inter-rill erosion.



**Fig. 3** The spatial distribution of soil water erosion and deposition as estimated using  $^{137}\text{Cs}$  measurements for the field at Huldberg.

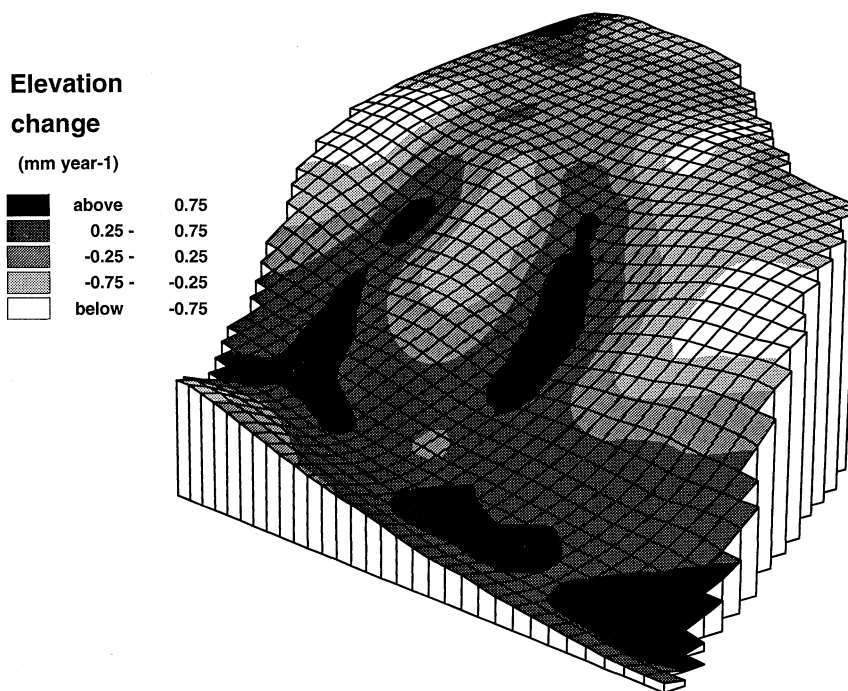
## IMPLICATIONS FOR SEDIMENT EXPORT

Although cultivation processes may lead to some displacement of soil beyond the field boundaries, this will be of very limited significance in relation to net export and will not contribute to sediment delivery to the fluvial system. In contrast, water erosion may be expected to play an important role in sediment export and the  $^{137}\text{Cs}$ -derived estimates can be used to quantify its impact. In order to take into account the marked variations in erosion rates over the sampled area, the calculations of sediment export have been undertaken for subsections, again excluding the boundary points. The areas subject to

**Table 1** Measures of water erosion derived for sub-sections of the sampled area using  $^{137}\text{Cs}$  data.

Sub-section:	Main thalweg	Zero-order slope concavities	Main body
Area (ha)	0.17	0.35	1.75
Erosion rate ( $\text{t ha}^{-1} \text{ year}^{-1}$ )	40.44	12.52	0.08
Mass exported ( $\text{t year}^{-1}$ )	6.87	4.41	0.14
Volume exported ( $\text{m}^3 \text{ year}^{-1}$ )	5.09	3.27	0.10
Field observation ( $\text{m}^3 \text{ year}^{-1}$ )	5-10	1.5-4	NA
Area (%)	7.5	15.5	77.0
Fraction of sediment export (%)	60.2	38.6	1.2

the highest water erosion rates (groups 2 and 3 in Fig. 2) have been identified and reclassified, according to topographic context, to form two new groups namely the main thalweg and the zero-order slope concavities. The final group represents the main body of the field (group 1 in Fig. 2). For each of these subdivisions of the field, the erosion rate and the area represented by the samples have been calculated and the data are summarized in Table 1. These data show an excellent agreement with the erosion estimates based on field observations which are also shown in Table 1.

**Fig. 4** The change in surface elevation over the study field over the last 35-40 years, as estimated using  $^{137}\text{Cs}$ .



By demonstrating the very marked spatial variation in water erosion rates, these data have clear implications for sediment export. The most important area of the field with regard to sediment export is the main thalweg, representing only 7.5% of the area but responsible for 60% of sediment export. Erosion in this area of the field is largely a result of runoff from adjacent cultivated areas. Reduction of runoff and of incision in this area, possibly through the use of grassed waterways (Baade *et al.*, 1993), may be expected to significantly reduce sediment export from this field.

## IMPLICATIONS FOR LANDFORM DEVELOPMENT

Having obtained quantitative estimates of water erosion and tillage redistribution rates it is possible to combine the values to calculate the net rates of surface lowering and aggradation over the last 35–40 years and, therefore, to examine the contemporary pattern of landform development (Fig. 4). If water erosion was the dominant process, the landscape would be characterized by increased incision of the concavities and thalweg, and a gradual increase in slope angle on the spurs. In contrast, tillage produces maximum erosion on the spurs, leading to reduced slope angles, and infilling of the hollows. The pattern shown in Fig. 4 indicates that the annual infilling of the slope concavities and the main thalweg by sediment displaced through tillage more than compensates for the lower frequency but more visible rill and gully incision. Overall, the pattern indicates that, despite the high susceptibility of this area to water erosion, landform development in this agricultural landscape is currently dominated by tillage processes resulting in a reversal of the expected landscape evolution with the gradual obliteration of topographic features.

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