An investigation of the influence of edaphic, topographic and land-use controls on soil erosion on agricultural land in the Borrowdale and Chinamora areas, Zimbabwe, based on caesium-137 measurements

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Abstract Soil erosion on agricultural land in two contrasting areas near Harare, Zimbabwe, has been investigated using caesium-137 (^{137}Cs) measurements. The Borrowdale area is characterized by commercial farming and tropical red soils. In contrast, the Chinamora study area is characterized by communal farming and granitic sandy soils. Inter-site contrasts provide an opportunity to examine the influence of land-management and edaphic controls upon erosion at the regional scale. Analysis of intra-site patterns also provides the basis for assessing local controls. In each study area, the role of topographic controls has been assessed by sampling a selection of fields displaying a representative range of topographic attributes. In the Chinamora area the erosional impacts of both pastoral and arable agriculture were examined by sampling grazing land and cultivated fields.The resultant data illustrate the complexity of the erosion pattern and the severity of the problem, and also demonstrate the applicability of the ^{137}Cs technique for reconnaissance level investigation of erosion.

INTRODUCTION

The severity of soil erosion on arable land and its potential impact on crop productivity in Zimbabwe has been highlighted by Elwell (1984). Using the SLEMSA estimator and a soil life-span model, Elwell predicted that the productive potential of large tracts of cropland would be destroyed within 30-50 years. In the light of this prediction it is clearly imperative that data are gathered regarding the actual rates of soil erosion and their distribution within the landscape. To obtain this information using erosion plots would require an inordinate level of investment, and Elwell (1984) suggests that 50 000 plots would be required to analyze the most common field conditions in Zimbabwe. Furthermore, the delay in obtaining representative data from plot monitoring limits the applicability of this approach in the development of land management strategies. Similarly, estimation of erosion rates through rill survey is inappropriate as soil loss is dominated by sheet erosion, because rilling and gullying have been controlled by mechanical protection (Elwell, 1984, 1990). In response to this need for data and the inapplicability of conventional methods of soil loss estimation the authors have used the caesium-137 (^{137}Cs) technique to investigate soil erosion on commercial arable land at Borrowdale, and on both pastoral and arable communal land in the Chinamora area. The technique offers the potential for obtaining long-term (*c.* 35 year) average estimates of net, gross and mean erosion rates, for identifying patterns of soil redistribution and for calculating sediment delivery ratios. A brief outline of the technique is provided in the next section which is followed by a description of the study areas and discussion of the estimated erosion rates. Finally, the significance of the rates is assessed in the context of topographic, land-use and edaphic controls.

THE CAESIUM-137 TECHNIQUE

Caesium-137 is an artificial radionuclide with a half-life of 30.17 years which was produced as a by-product of atmospheric testing of thermo-nuclear weapons, primarily from the mid-1950s to the mid-1970s. The ^{137}Cs was released into the stratosphere, distributed globally and deposited as fallout, usually in association with precipitation. Its value as a sediment tracer lies in its high affinity for soil particles, particularly the clay fraction (Bachhuber *et al.*, 1982; Livens & Baxter, 1988), such that in most agricultural environments lateral redistribution after initial deposition takes place only in association with sediment. Assessment of ^{137}Cs redistribution is commonly based upon comparison of measured inventories (total activity per unit area) from the sampled site with an equivalent estimate of the cumulative atmospheric deposition. As direct measurements of atmospheric deposition to a site are rarely available, the cumulative input or reference inventory is commonly established by sampling nearby undisturbed, uneroded locations supporting permanent grassland. Where sample inventories are lower than the local reference level, loss of ^{137}Cs-labelled soil and therefore erosion may be inferred. Similarly, sample inventories in excess of the reference level are indicative of addition of ^{137}Cs-labelled soil by deposition. The magnitude and direction of measured deviations from the local reference level provide a qualitative assessment of sediment redistribution.

In order to derive quantitative estimates of rates of soil erosion and aggradation from ^{137}Cs measurements, it is necessary to establish empirical or theoretical relationships between the magnitude of the deviation from the reference inventory and the extent of soil loss or gain. As empirical calibration data are rarely available, the authors have developed a numerical model which represents the redistribution of ^{137}Cs associated with soil erosion and aggradation on arable fields (Quine, 1989; Walling & Quine, 1990). This model can be used to simulate the effect of a range of long-term erosion and aggradation rates upon the ^{137}Cs inventory of soil profiles and such data are then used to derive calibration relationships. In order to establish calibration relationships for profiles on pastoral land, the model was adapted to account for downward migration of ^{137}Cs in the absence of cultivation mixing.

Samples of soil for ^{137}Cs measurement were collected for this study using two methods. Where ^{137}Cs inventories were required, bulk samples were collected using a 6.9 cm diameter core tube which was propelled into the ground using a motorized percussion hammer to a depth of 50 to 60 cm. Sampling to this depth ensured that the total ^{137}Cs inventory of the soil profile was measured. Where information on the depth distribution of ^{137}Cs was required, depth incremental samples were collected using a 'scraper-plate' (Campbell *et al.*, 1988) with a surface area of 640 cm^2. All samples were air-dried, disaggregated, passed through a 2 mm sieve and weighed. The ^{137}Cs content was measured on the <2 mm fraction by gamma spectrometry using a coaxial germanium detector and multi-channel analyzer system. Caesium-137 was detected at 662 keV and counting times, which were typically about 55 000 s, provided results with an analytical precision of approximately $\pm 15\%$ (2 S.D.).

THE STUDY AREAS

Two study areas were selected for investigation using ^{137}Cs. The first was the Institute of Agricultural Engineering Farm at Borrowdale (17°45'S, 31°5'E), on the northern edge of Harare, which was selected as being representative of commercial farming on tropical red soils. These soils area described as inherently fertile clay loams and clays in the legend of the soils map of the Federation of Rhodesia and Nyasaland (Thompson *et al.*, 1960), but they show a marked change in erodibility with management (Elwell, 1986, 1990). The Institute Farm is divided into large blocks which formerly contained individual fields. In the period from 1970 onwards, these blocks were divided into contour strips in an attempt to reduce rill and gully erosion. As rates of erosion derived using ^{137}Cs represent the aggregate effect of all processes of soil redistribution operating during the period since 1954, it is important to consider this change in land-division when interpreting the measured rates. The two blocks which were sampled, namely numbers 1 and 2, were divided into contour strips in 1972. Therefore, the pattern of soil redistribution derived using ^{137}Cs represents the impact of erosion within the contour strips for a period of 19 years, superimposed on the pattern of erosion developed in the larger fields over 18 years prior to structural subdivision. Despite the similar length of the two periods, the pattern of soil redistribution identified using ^{137}Cs may be dominated by erosion processes operating during the earlier period as it includes the phase of most significant atmospheric fallout, and therefore most intensive ^{137}Cs redistribution (Quine, 1989). Although the land-use history of this site complicates the interpretation of the results, it is representative of the majority of the commercial farming land in the region which underwent such changes during the same period.

Transects of core samples were collected through the contour strips of blocks 1 and 2 and one contour strip in block 1 was sampled in detail to investigate within-field patterns of soil redistribution. The transects were aligned along the line of greatest slope, perpendicular to the buffers which divided the contour strips. Transect 1 was 560 m long with a slope angle 1.8° and transect 2 was 570 m long with an overall slope of 2°. In the descriptions of individual contours, the strip length is defined as the length along the line of greatest slope. Along transect 1 the uppermost eight strips were *c.* 30 m in length, and the remaining six were *c.* 40 m. Slope angles varied from 2.5° to 1.6°. Along transect 2, the longest strips were 1 and 7 at 60 m and the shortest was 4 at 30 m, the remaining strips were *c.* 40 m long within the upper part of the transect and *c.* 50 m long within the lower section. Slope angles along transect 2 varied from 3.3° to 1.3°.

The second study area at Chinamora (17°37'S, 31°15'E), 20 km to the northeast of Borrowdale, was chosen as representative of communal agricultural land on the leached, inherently infertile sandy soils developed on granite (Thompson *et al.*, 1960).

Transects of core samples were collected from arable fields in continuous use, arable fields which had been converted back to pasture, and from permanent pasture which was characterized by sparse woodland and more diverse topography. One cultivated field was sampled in detail as at Borrowdale. The cultivated fields which were sampled varied in length from 12 to 60 m and in slope angle from 1.4° to 6.5°. The previously cultivated fields were longer, varying from 27 to 83 m, but had lower slope angles, from 1.8° to 3.8°. At the permanent pasture site, slope angles varied from 2.5° to 4.5° on the ridges and from 2.1° to 3.8° in the lower-lying seasonally marshy area known as a vlei.

In addition to the transects of core samples, depth incremental samples were collected from undisturbed and cultivated soil profiles at both Borrowdale and Chinamora. These incremental samples allow examination of the depth distributions of ^{137}Cs from these locations (Fig. 1). The distributions associated with the undisturbed profiles (Fig. 1(a) and (b)) show the expected sharp decline in ^{137}Cs activity with depth which is indicative of effective adsorption of the ^{137}Cs in the surface horizon. Core samples from the undisturbed locations provided estimates of the reference inventory of 30 mBq cm^{-2} at both sites. The profile distributions associated with cultivated soils (Fig. 1(c) and (d)) show ^{137}Cs mixed throughout the plough layer, which is consistent with expectations and the fundamental assumptions of the ^{137}Cs technique (Walling & Quine, 1992). These results confirm the applicability of the technique in this environment.

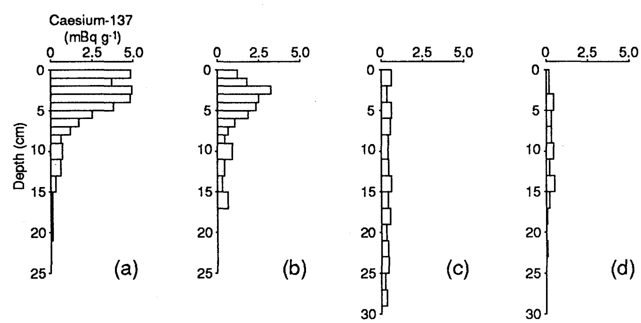

Fig. 1 Depth distributions of ^{137}Cs from undisturbed locations at (a) Borrowdale and (b) Chinamora, and from cultivated locations at (c) Borrowdale and (d) Chinamora.

RESULTS

It is possible to obtain a range of erosion rate data using the ^{137}Cs technique (Quine & Walling, 1991). Values of net, gross and mean erosion rates, percentage eroding length and sediment delivery ratio are used in the discussion and are defined as follows: net rates of soil erosion represent the total amount of soil exported from the cultivated area, divided by the total cultivated area; gross rates represent the total amount of soil eroded within the cultivated area divided by the total cultivated area; and mean rates represent the total amount of soil eroded within the cultivated area divided by the area subject to erosion; the percentage eroding length represents the fraction of the area subject to net soil loss; sediment delivery ratios express the fraction of eroded sediment exported from the cultivated area and are calculated as the ratio of net to gross erosion.

It is important to note that some of the sediment exported from the cultivated area may be deposited against field boundaries or in ditches and the sediment delivery ratio, as here defined, does not necessarily represent the fraction of sediment reaching the fluvial system.

EROSION ON CULTIVATED LAND

Transect data from Borrowdale

The various erosion rate measures derived for each of the contour strips along transects 1 and 2 are summarized in Table 1 with information on the slope angle and length of the strips. These data indicate that there is no simple relationship between the erosion rate measures and these topographic attributes. The absence of correlation is not surprising in view of the history of the site and the following discussion examines the erosion rate data in the context of the change in land-division.

The data for transect 1 suggest that block 1 was initially divided into two segments, representing contour strips 3 to 9 and 10 to 14, each characterized by erosion over the upper length and deposition in the lower part. The erosion rate measures may be calculated for these two segments and these are also summarised in Table 1. These data show a slightly higher net rate of soil loss, sediment delivery ratio and percentage length subject to erosion for the upper segment compared to the lower. All of these are consistent with the greater slope length and angle of the upper segment. The higher gross and mean erosion rates for the lower segment may be attributed to the very high rates of erosion from contour strip 10.

The data for transect 2 suggest that strips 1 to 5 may have formed a single unit similar to the upper segment of transect 1. The combined statistics for the segment of transect 2 composed of strips 1 to 5 are listed in Table 1 and show similar gross and mean erosion rates to those identified for the upper segment of transect 1, but a lower net rate of erosion and sediment delivery ratio reflecting the more extensive depositional zone. The development of this zone may have been influenced by the presence of the woodland on the west and southwest border of this part of block 2.

The net rates of erosion for the remaining 6 strips of transect 2 alternate between values in excess of 30 t ha^{-1} $year^{-1}$ and values between 3 and 11 t ha^{-1} $year^{-1}$. This may reflect a former division of this part of block 2 into three 100 m long segments, each composed of a pair of the current contour strips. If the strips are divided in this manner a remarkable degree of consistency is found (Table 1), with net rates varying between 16 and 23 t ha^{-1} $year^{-1}$ and mean rates between 23 and 26 t ha^{-1} $year^{-1}$.

Table 1 also provides summary statistics for the whole of transects 1 and 2, and for transect 1 to the base of contour 11, which is the equivalent position on the slope to the base of transect 2. Despite the different patterns seen in the individual strip data for the two transects, the summary data are very similar and suggest that above the depositional zone represented by contour strips 12 to 14 of transect 1, the slopes are typified by erosion over more than 70% of the area at mean rates of loss between 16 and 21 t ha^{-1} $year^{-1}$. Even when the depositional zone is taken into account the sediment delivery ratio for the whole of transect 1 is close to 70% and the net erosion rate exceeds 6 t ha^{-1} $year^{-1}$.

Table 1 Erosion rate data for contour strips and blocks at Borrowdale.

no	**Strip** length (m)	angle (deg.)	**Erosion rates** (t ha^{-1} year^{-1}) net*	gross	mean	**Sediment Delivery Ratio %**	**Eroding Length %**
Block 1							
4	71	2.2	11.0	12.7	36.1	87	35
5	22	2.1	13.3	16.7	24.3	80	68
6	29	1.9	4.0	4.0	4.0	100	100
7	30	1.8	4.3	4.3	4.3	100	100
8	35	1.9	8.7	8.7	8.7	100	100
9	38	2.0	-4.0	0.8	1.5	0	51
10	38	1.6	39.3	39.3	39.3	100	100
11	41	1.7	2.4	4.8	8.9	51	54
12	39	1.7	-0.3	0.7	1.5	0	50
13	40	2.5	-11.5	0.0	0.0	0	0
14	34	2.2	0.8	6.3	11.3	12	56
Block 2							
1	60	3.3	-0.7	3.6	9.6	0	37
2	37	2.9	6.5	6.8	9.0	97	75
3	37	2.3	21.8	21.8	21.8	100	100
4	30	2.1	-10.8	1.0	4.9	0	19
5	38	2.0	-4.2	5.6	9.2	0	60
6	35	1.3	31.3	31.7	44.0	99	72
7	61	1.6	7.5	9.4	14.6	80	65
8	50	1.8	42.1	42.2	42.2	100	100
9	50	1.7	3.9	3.9	3.9	100	100
10	47	1.5	36.0	36.1	36.1	100	100
11	46	1.5	10.5	10.5	11.1	99	95
Block 1 Segments							
3-9	319	1.9	6.5	8.2	12.0	80	68
10-14	229	1.7	6.1	9.9	19.4	61	51
Block 2 Segments							
1-5	231	2.5	3.0	7.7	13.1	39	59
6-7	106	1.7	16.2	17.5	26.0	92	67
8-9	105	1.7	23.0	23.0	23.0	100	100
10-11	102	1.6	23.4	23.4	24.0	100	97
Block 1 Total							
3-14	559	1.8	6.3	9.0	15.0	69	60
3-11	419	1.8	10.1	11.6	16.5	87	70
Block 2 Total							
1-11	570	2.0	13.4	15.6	20.6	86	76

* (Negative erosion rates in the net erosion column represent net aggradation)

Detailed field data from Borrowdale

As indicated above, one contour strip was sampled in detail to allow examination of within-field patterns of soil redistribution. The strip selected was number 11 on transect 1 which lies at the interface between the high erosion rates found on the area covered by strip 10 and the depositional zone now represented by contours 12 to 14. The pattern of soil redistribution (Fig. 2) reflects this position with 53% of the strip being

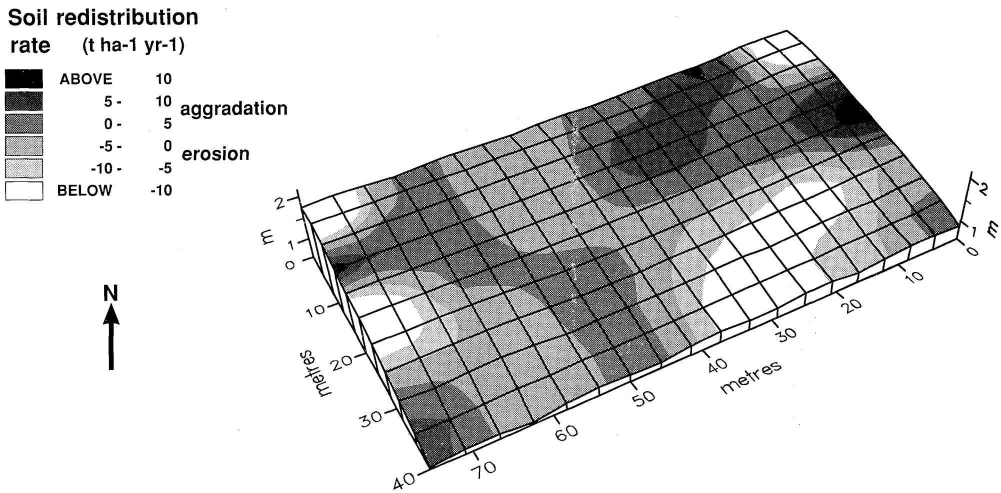

Fig. 2 The pattern of within-field soil redistribution superimposed upon topography for contour strip 11 of block 1 at Borrowdale.

relatively stable, characterized by redistribution rates between -5 t ha^{-1} $year^{-1}$ (erosion) and -5 t ha^{-1} $year^{-1}$ (aggradation). However, the irregular form of the eroding and aggrading zones does not appear to reflect the near uniform nature of the contour strip. Instead the pattern of erosion would be consistent with localized runon forming linear zones of erosion across the strip. This could have occurred prior to subdivision of the block or since formation of the contour strips through a breach in the upslope buffer strip. Whichever explanation is correct the pattern highlights the role of erosive flow generated outside the contour strip and therefore detailed interpretation of within-field topographic controls on soil redistribution is not appropriate.

Transect data from Chinamora

The sampled transects at Chinamora were shorter and included fewer fields than those at Borrowdale, because the continuously cultivated fields are more dispersed. Four transects were sampled, one containing four fields, two with three fields, and one with two fields. The data for each of the transects are included in Table 2. As at Borrowdale, there is no clear relationship between erosion rates and slope length or angle. However, consideration of the transects individually reveals some meaningful trends. In the case of transect 1, fields 2 to 4 show an increase in net erosion rate with both field length and angle, but field 1 has a lower than expected erosion rate. The presence of permanent grassland and woodland at the upslope boundary of field 1, reducing the amount of run-on, may be responsible for this lower rate. The erosion rates observed on fields 1 and 2 of transect 2 appear very high in view of the low slope angle. However, there are no structural divides between the fields of this transect and therefore no impediment to overland flow. The pattern is therefore one of increasing erosion with increasing slope length, from field 1 to 2, with some limited sediment deposition in the low-lying area at the base of the transect represented by field 3. Transect 3, like transect 1, is bounded by woodland at the upper edge and this may

Table 2 Erosion rate data for cultivated fields at Chinamora.

no	Field length (m)	angle (deg.)	Erosion rates ($t\ ha^{-1}\ year^{-1}$) net*	gross	mean	Sediment Delivery Ratio %	Eroding Length %
Transect 1							
1	25	4.3	10.4	23.8	31.7	44	75
2	30	3.4	28.7	28.7	28.7	100	100
3	16	2.8	13.4	19.6	28.9	68	68
4	20	3.2	16.3	18.4	21.0	88	88
total	125	3.7	18.3	23.5	27.7	78	85
Transect 2							
1	63	1.4	32.7	32.7	32.7	100	100
2	25	1.4	46.0	46.0	46.0	100	100
3	30	3.4	-3.3	0.0	0.1	0	2
total	115	1.9	27.4	28.1	36.2	97	78
Transect 3							
1	21	6.5	13.3	16.4	26.7	81	62
2	10	5.5	23.5	23.7	25.8	99	92
total	34	6.3	16.7	18.8	26.3	89	71
Transect 4							
1	42	1.2	27.8	28.6	33.9	97	85
2	26	1.6	15.4	16.0	17.8	96	90
3	28	0.8	16.8	16.8	16.8	100	100
total	100	1.2	21.3	21.8	24.1	98	91

* (Negative erosion rates in the net erosion column represent net aggradation)

again be partially responsible for the lower than expected erosion rate on field 1. Finally transect 4 is now surrounded by an area that has reverted to pasture, but would formally have been cultivated, the current slope length therefore masks a formerly much greater effective slope length, broken only by relatively small buffer strips.

Detailed field data from Chinamora

Detailed sampling of field 4 of transect 1 allows examination of the pattern of within field soil redistribution (Fig. 3). This pattern shows 63% of the field subject to rates of erosion in excess of 5 $t\ ha^{-1}\ year^{-1}$ and 30% with rates in excess of 25 $t\ ha^{-1}\ year^{-1}$. However, one of the clearest features of the pattern is its irregularity. If erosion and deposition were solely controlled by processes operating within the field boundaries, then a regular pattern would be expected across this relatively uniform slope. Instead, the most severe erosion extends in a zone from the middle of the upper boundary of the strip to the lower east corner.

This pattern is consistent with erosion induced by runon passing diagonally across the field. A second zone of erosion lies in the upper northern corner of the field and may be the result of runon from the footpath which lies 5 m to the east along the border of the field. The localized area of net aggradation at the lower boundary of the field is consistent with accumulation through cultivation displacement and sediment

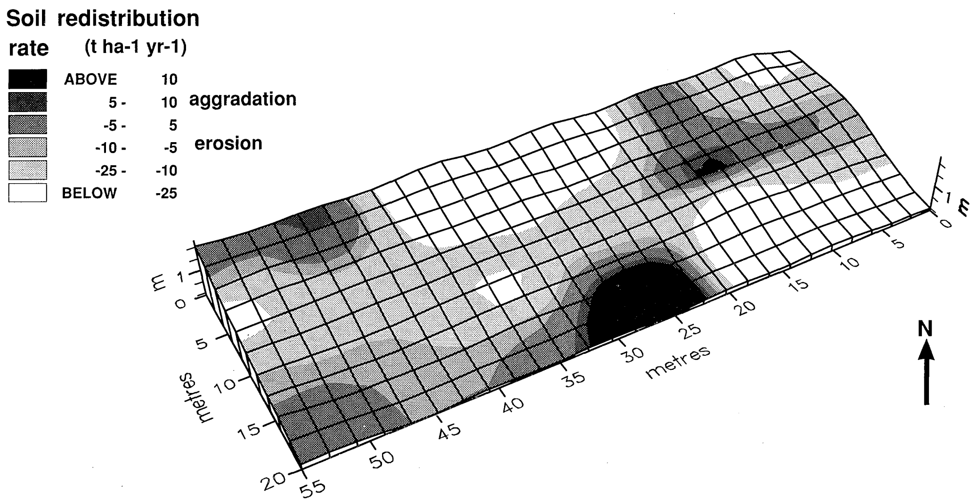

Fig. 3 The pattern of within-field soil redistribution upon topography for field 4 of transect 1 at Chinamora.

trapping against the field boundary. The overall pattern of soil redistribution highlights the importance of runon from areas beyond the field boundary and the necessity of examining individual field data in the context of the transect.

Erosion on grazing lands at Chinamora

Two transects of core samples were collected from permanent grazing land used by the Chinamora community. The first transect followed a sparsely wooded ridge to the edge of more dense woodland, and the second traversed the side of the same ridge and followed the drainage course into a vlei. The erosion rates and topographic data for both transects are summarised in Table 3. These data show a high degree of consistency, with soil loss of *c.* 4 t ha^{-1} $year^{-1}$ from the ridges and side slopes, minimal deposition close to the ephemeral channel and extensive deposition on the vlei floor, particularly at the upslope limit. The absence of large scale topographic maps precludes calculation of the percentages of the area covered by ridges and vleis, so it is not possible to provide an accurate assessment of rates of soil export from the grazing land. However, if it is assumed that vleis cover less than 25% of the total area, then it might be anticipated that rates of export could lie between 2 and 3 t ha^{-1} $year^{-1}$.

In addition to the transects on permanent grazing land, one transect was located on previously cultivated land which had reverted to pasture for *c.* 10 years. This land is still divided by buffer strips and unlike the permanent pasture it is devoid of trees. The erosion rates and topographic data for this transect are listed in Table 4.

The long-term average erosion rates are similar to those found on the continuously cultivated land, despite the extended fallow period, reflecting the intensity of erosion during the period of cultivation. If it is assumed that during the period since the cessation of cultivation the net erosion rates have been only slightly higher than those on the permanent pasture at about 5 t ha^{-1} $year^{-1}$, the calibration model can be rerun

Table 3 Erosion rate and topographic data for the transects on permanent grazing land at Chinamora.

Site	Transect distance (m)	Upslope angle (deg.)	Erosion rate (t ha^{-1} year^{-1})	Topographic context
Transect 1				
1	0	2.7	7.8	ridge
2	30	3.0	4.3	ridge
3	60	3.3	0.8	ridge
4	90	4.5	4.4	ridge - near path
5	120	3.4	-3.8	ridge - woodland edge
Transect 2				
1	0	5.2	2.0	ridge
2	33	4.3	6.1	ridge
3	70	4.6	-2.4	adjacent to ephemeral channel
4	102	3.3	-1.3	adjacent to ephemeral channel
5	138	5.9	-2.7	close to channel at base of step
6	177	2.1	-13.8	upslope end of level vlei
7	213	3.8	-5.9	vlei centre
8	250	2.3	-4.5	vlei centre
9	286	4.1	-4.7	vlei centre

Table 4 Erosion rate data for the transect on formerly cultivated fields at Chinamora.

no	Field length (m)	angle (deg.)	Erosion rates (t ha^{-1} year^{-1}) net		gross		mean		Sediment Delivery Ratio %		Eroding Length %	
Estimates to:			91	81	91	81	91	81	91	81	91	81
1	50	3.8	19.9	28.2	19.9	28.2	19.9	28.2	100	100	100	100
2	35	2.9	17.2	29.4	21.1	31.3	29.5	40.6	81	94	71	77
3	27	2.3	7.9	14.4	11.4	16.2	16.5	22.7	69	88	69	72
4	44	1.9	21.2	33.5	22.9	34.3	30.4	43.9	93	97	75	78
5	75	1.8	8.7	16.8	12.9	19.1	23.5	33.0	68	88	55	58
6	83	2.0	13.7	21.0	14.9	21.4	16.7	23.0	92	98	89	93
all	319	2.2	14.7	23.6	16.9	24.7	22.0	30.9	87	95	77	80

and the rates of erosion during the period of cultivation may be calculated. These recalibrated values are also included in Table 4 and they can be seen to be more closely in line with the rates of erosion on the continuously cultivated fields.

EROSION RATES AT BORROWDALE AND CHINAMORA

This study has attempted to provide quantitative assessments of the rates of soil erosion on agricultural land at two sites near Harare, Zimbabwe, and to identify the primary controls of those rates. Examination of edaphic controls was limited to investigation of cultivated fields on two broad soil types representative of the region, the red clay-rich soils at Borrowdale and the granitic sandy soils at Chinamora. It should be noted that the edaphic contrast is accompanied by a management contrast, because commercial practices are employed at Borrowdale, whereas Chinamora lies in the communal lands. However, it was expected that the high erodibility of the sandy soils and the pressure on land at Chinamora would lead to the identification of higher erosion rates there than at Borrowdale, despite the greater field lengths and increased mechanization employed on the clay soils. The results were in accord with this expectation, with net rates for the four cultivated transects at Chinamora of 17, 18, 21 and 27 t ha^{-1} year^{-1}, compared to 6 and 10 t ha^{-1} year^{-1} at Borrowdale. The gross rates of 9 and 16 t ha^{-1} year^{-1} at Borrowdale, compared to 19, 22, 23 and 28 t ha^{-1} year^{-1} at Chinamora reinforce this contrast. However, the rates at both sites give cause for concern in relation to sustained productivity. At Borrowdale, the impacts will be less severe due to the inherent fertility of the parent material. At Chinamora the gross rates of erosion are about 20 times greater than the rate of soil formation and 4 times greater than the estimated acceptable soil loss of 5 t ha^{-1} year^{-1} (Elwell, 1984) and are, therefore, potentially catastrophic. In 1984, Elwell suggested that subsistence yields could be threatened within 30 years, based on an estimated soil erosion rate of 50 to 80 t ha^{-1} year^{-1}. Although the rates derived using ^{137}Cs for Chinamora are lower, they do suggest that subsistence yields may be threatened before the middle of the next century. Furthermore, serious off-site impacts may be predicted on the basis of the very high sediment delivery ratios at both sites, 69 and 86% for the two transects at Borrowdale, and 78, 89, 97 and 98% at Chinamora. Although some of the exported sediment may be trapped by field boundaries, the data suggest that a very significant proportion of the sediment will reach the fluvial system.

The assessment of potential topographic controls on erosion has been addressed in the discussion of the individual sites by examining the topographic variables which are most commonly used in erosion hazard assessment and modelling, namely slope length and steepness. The discussion has identified the absence of any consistent relationship between the rates of erosion, identified for individual fields or contour strips, and the topographic variables either individually or in combination. The pattern of erosion along all of the cultivated transects could only be understood in the context of the whole transect. At the Borrowdale site this partly reflects the history of the site, with a change from larger fields to smaller units. However, at Chinamora both the transect data and the detailed field study showed the importance of position on the transect and the location of the transect as a whole. These findings suggest that simple models used in erosion hazard assessment may be adequate at the regional scale, but that when local management decisions are required, such models must be refined to account for local conditions or quantitative data must be gathered. If the latter course is taken, then it would appear that the ^{137}Cs technique is one of the few approaches which can provide the necessary data.

The influence of land-use on erosion was assessed by investigating rates of erosion from both cultivated land and permanent pasture at Chinamora. The resultant data identify much lower rates of erosion on the pasture than the arable fields and it is suggested that rates of erosion over much of the pasture are of the order of 4 t ha^{-1} year^{-1}, and therefore only 15 to 25% of the gross rates of soil loss on the cultivated transects. Furthermore, the study identified the importance of vleis as sediment traps, so that a tentative estimate of net soil loss from pasture of the type studied would be *c.* 2 t ha^{-1} $year^{-1}$. This represents a relatively minor off-site threat, but the suggested rate of erosion of 4 t ha^{-1} $year^{-1}$ over much of the pasture area is 4 times the estimated rate of soil formation (Elwell, 1984), and therefore suggests that the current grazing intensity is too high to be supported indefinitely.

Studies of erosion at Borrowdale and Chinamora using ^{137}Cs have provided quantitative assessments of the rates of erosion from both arable land and pasture. The data illustrate the complexity of the erosion pattern and the severity of the problem, and also demonstrate the applicability of the ^{137}Cs technique for reconnaissance level investigation of erosion.

Acknowledgements The work reported here was undertaken as part of a project funded by the UK Overseas Development Administration. This funding and the assistance of Dr Henry Elwell and Mr Paul Gotora with fieldwork logistics is gratefully acknowledged. Thanks are also due to Mr Phil Owens for help with sample collection and Mr Jim Grapes for assistance with gamma spectrometry, and to MAFF for authorizing a licence (PHF/160/67/32) to import soil samples.

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