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The use of caesium-137 measurements in soil erosion surveys

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ABSTRACT Accelerated erosion and associated soil degradation represent major problem for the global environment. There is an increasing need to assemble reliable information on recent rates of soil loss, but existing measure ment techniques possess many limitations. The caesium-137 technique, which is able to provide retrospective estimates of longer-term (ca. 35 year) erosion rates over extended areas based on a single site visit, would appear to offer considerable potential. Several of the basic assumptions of the technique are reviewed and substantiated and examples of its application in both detailed studies of individual fields and catchment-scale reconnaissance surveys are provided. Future development of the approach could usefully focus on development of sampling and extrapolation strategies for use in reconnaissance surveys.

INTRODUCTION

Although much of the recent concern for the global environment has focussed on problems of global warming and climatic change, there is also increasing evidence that accelerated erosion and associated soil degradation represent a major problem for the sustainable development of agricultural production in a world characterized by a rapidly expanding population. Brown (1984), for example, estimated that the world is currently losing 23 billion tonnes of soil from croplands in excess of new soil formation each year. This is equivalent to a depletion of the global soil resource by 7% each decade. Buringh (1981) also estimated an annual global loss of agricultural land due to soil erosion of 3 million ha. Soil erosion has serious implications for agricultural productivity, but there are also many other off-farm or downstream problems associated with increased sediment loads in rivers, including reservoir sedimentation (cf. Clark *et al.*, 1985).

Against this background there is an increasing need to assemble reliable information on recent rates of soil loss as a means of assessing the magnitude of the problem in particular areas, obtaining a better understanding of the environmental controls involved and developing conservation measures and improved land management strategies. Existing techniques for monitoring soil erosion do, however, possess many limitations in terms of their potential to provide information on longer-term rates of soil loss over extended areas (cf. Loughran, 1990). Because of these limitations, the caesium-137 technique for investigating rates and patterns of erosion has been applied in many areas of the world and has attracted considerable interest and enthusiasm since its development by Ritchie and McHenry in the USA (cf. Ritchie *et al.* 1974). In essence, the technique provides a means of assembling information on long-term (ca. 35 year) rates of soil loss and spatial patterns of erosion for an area based on a single site visit (cf. Walling & Quine, 1991). This paper attempts to provide a general assessment of the potential for wider application of the approach in soil erosion surveys.

THE CAESIUM-137 TECHNIQUE

As a result of more than 20 years of application, the caesium-137 technique has become established as an important tool for investigating soil erosion and recent work has demonstrated that it can be used in a wide variety of environments (Fig. 1). The basis of the technique is now well documented

(cf. Campbell, 1983; Walling & Quine, 1991) and further discussion of its basis can usefully focus on several key assumptions which are fundamental to its successful application. These are as follows:
(a) Uniform local fallout distribution.
(b) Rapid adsorption of caesium-137 fallout onto soil particles.
(c) Subsequent redistribution of caesium-137 reflects sediment movement.
(d) Estimates of rates of soil loss can be derived from measurements of soil caesium-137 inventories.

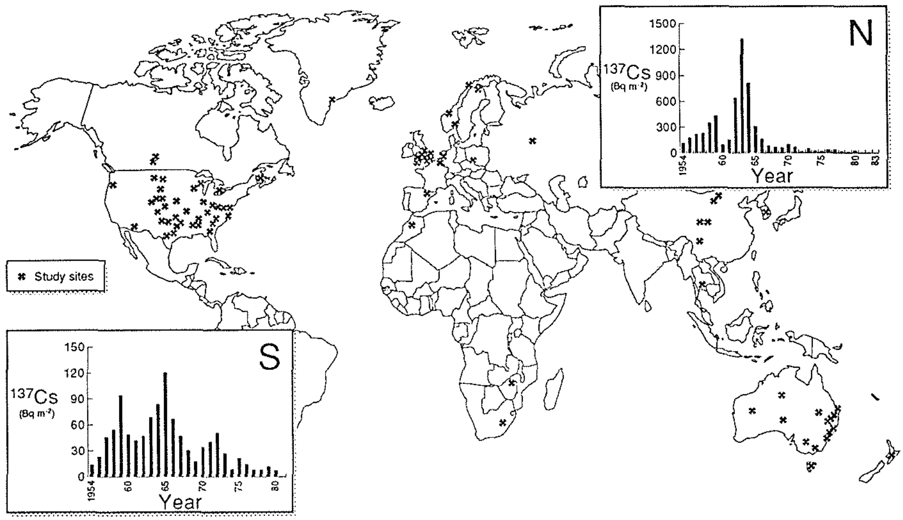

FIG. 1 Locations where caesium-137 has been successfully used in soil erosion studies and typical fallout records for the northern (New York, USA/Milford Haven, UK) and southern (Adelaide/Brisbane, Australia) hemispheres.

Spatial distribution of caesium-137 fallout

Caesium-137 was released into the global environment as a result of the testing of thermonuclear weapons, most of which took place from the mid-1950s to the mid-1970s. The radioactive debris associated with the weapons testing was propelled into the stratosphere and thereby distributed globally. Fallout deposition occurred mainly in association with precipitation and reached a maximum during the period 1954-1968. This deposition exhibited latitudinal global variation in response to the distribution of bomb tests, with higher levels in the northern hemisphere than the southern hemisphere (cf. Fig. 1). Regional patterns of deposition typically reflect variation in annual precipitation.

The assumption of a locally uniform fallout distribution and the establishment of a fallout baseline for a study area is central to the assessment of caesium-137 redistribution, which represents the fundamental basis of the caesium-137 technique. The question of local variability is, therefore, critical. Although it is well known that precipitation may exhibit marked local variability at the level of the individual storm, it is generally assumed that over a period of several years, the superposition of the patterns from individual storms will result in an essentially uniform local pattern of total fallout. The assumption of spatial uniformity of local fallout inputs was questioned after the Chernobyl accident, when surveys demonstrated marked spatial variability in fallout levels. However, since the Chernobyl plume did not reach the stratosphere and the period of fallout was shortlived and associated with a very small number of precipitation events, these findings were not unexpected and it is inappropriate to make direct comparisons with patterns of weapons test fallout. There is little empirical evidence for the pattern and variability of weapons test fallout at the local scale and, until such data become available, the assumption of locally uniform deposition patterns must be accepted on the basis of the logic outlined above. However it is essential to establish the level of local fallout inputs with care and with regard to potential causes of variability such as snow drifting.

Caesium-137 adsorption

In contrast to the dearth of data relating to local patterns of deposition, there have been numerous laboratory and field investigations of the adsorption of radiocaesium by soil particles. Livens & Loveland (1988) cite the work of several investigators as demonstrating highly efficient extraction of radiocaesium from very dilute (0.001M) solutions by clay minerals. The radiocaesium concentrations in these solutions are several orders of magnitude greater than those associated with rainfall during the peak period of weapons test fallout and therefore suggest that fallout radiocaesium would have been rapidly fixed by clay particles in the upper horizons of the soil. The effects of soil texture and the magnitude of the clay fraction must also be considered, but other studies suggest that the proportions of fine particles commonly found in mineral soils do not limit radiocaesium adsorption. Livens & Baxter (1988) examined a range of soil types and found that radiocaesium was adsorbed by all the mineral soils investigated. Strong adsorption is also evidenced by the low rate of vertical migration of caesium-137 evident for many soil types in both field and laboratory experiments (cf. Bachhuber *et al.*, 1982; Frissel & Pennders, 1983; Squire & Middleton, 1966) and in the typical depth distributions of weapons test caesium-137 in undisturbed soil profiles (Fig. 2).

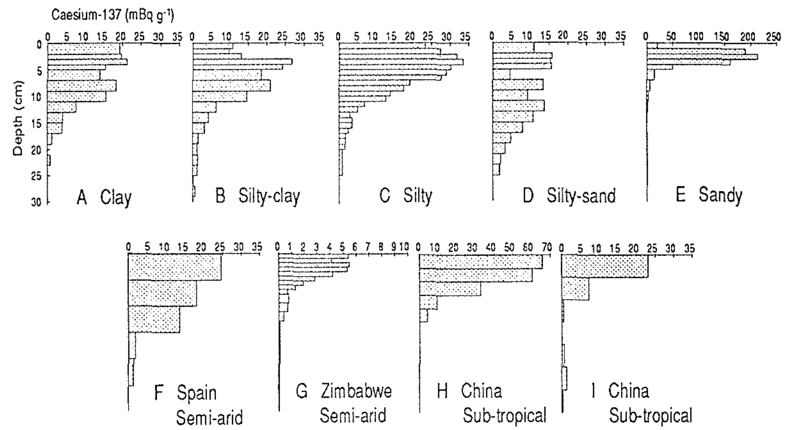

FIG. 2 Examples of typical caesium-137 profiles associated with undisturbed soils. A-E: soil textural variation in the UK; F-I: environmental variation, worldwide.

All of the caesium-137 profiles from these soils, which encompass a textural range from clay to sand in the UK (Fig. 2 A to E) and an environmental range from semi-arid to sub-tropical worldwide (Fig. 2 F to I), show a sharp decline in caesium-137 activity with increasing depth. In each case more than 75 % of the total inventory occurs in the top 15 cm, indicating that vertical translocation is minimal. Furthermore, the total inventories of the UK soils are in close agreement with existing evidence regarding total fallout amounts (cf. Cawse & Horrill, 1986). These profile characteristics support the assumption that in most environments the majority of mineral soils have the capacity to adsorb and immobilize fallout caesium-137. It must, however, be accepted that recent studies of the fate of Chernobyl fallout have indicated that acid organic soils in some upland locations may be characterized by slower and weaker fixing of radiocaesium, particularly at the high concentrations found in Chernobyl fallout, and that, in such circumstances, a significant proportion of the fallout input may be transported beyond the initial point of receipt.

Sediment-associated redistribution of caesium-137

A further critical assumption of the caesium-137 technique is that after the initial fixing of fallout radionuclides within the upper horizons of the soil, all subsequent redistribution of radiocaesium will take place in association with the movement of soil and sediment particles. Some of the earliest studies of caesium-137 mobility provided evidence to support this proposition. Rogowski & Tamura (1970) observed that 99% of the loss of caesium-137 from a bare Captina soil plot in Tennessee, USA, could be attributed to soil erosion. Subsequent studies have confirmed these findings.

The close equivalence between the caesium-137 inventories from undisturbed locations and independent assessments of atmospheric deposition, and the evidence of the profile distributions, both discussed in the previous section, support the proposition of insignificant loss of caesium-137 in the absence of erosion. Further indirect evidence of the close relationship between the movement of caesium-137 and soil particles is afforded by profile distributions from cultivated sites. In the absence of significant vertical or lateral translocation of caesium-137, it would be expected that the majority of the caesium-137 found in cultivated soils would be evenly distributed throughout the plough layer and that stable, eroding and aggrading sites would be clearly distinguishable. At eroding sites, loss of caesium-137 labelled soil from the surface would lead to depletion of the inventory and reduction of radiocaesium concentrations in the plough layer by incorporating soil, containing no radiocaesium derived from below the original plough depth. In contrast, at aggrading sites addition of caesium-137 labelled soil at the surface will lead to an increase in the inventory and burial of caesium-bearing soil below the plough depth. Over an extended period of time, this would lead to the formation of a stretched profile, with elevated levels of caesium-137 occurring well below the maximum depth of ploughing. In contrast, if lateral translocation of caesium-137 had occurred, in the absence of sediment redistribution, receiving sites would be characterized by increased caesium-137 inventories with no extension of the depth distribution. All of the caesium-137 profile distributions from cultivated sites investigated by the authors are consistent with sediment-associated transport of radiocaesium and the absence of significant lateral redistribution not associated with sediment movement. Figure 3 provides examples of profile distributions representative of cultivated sites on a range of soil types in the UK and of environmental conditions worldwide which support this proposition.

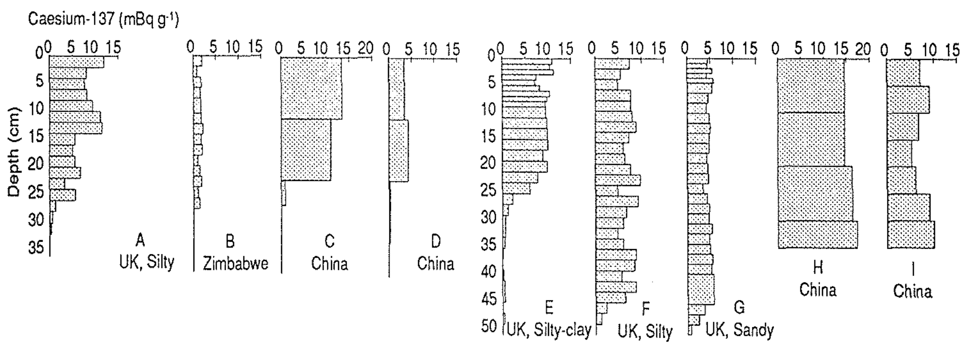

FIG. 3 Examples of typical caesium-137 profiles associated with cultivated soils. A-D: stable or eroding sites; E-I: aggrading sites. (Plough Depth: A, B, F, G 25cm C-E, H, I 20cm)

Estimating rates of soil loss from caesium-137 measurements

Use of caesium-137 measurements to estimate rates of loss and accretion is commonly based on the assumption that a reliable relationship can be established between the degree of increase or depletion of the soil caesium-137 inventory relative to the baseline inventory and the total depth of soil loss or accretion. Walling & Quine (1990) have recently reviewed many of the uncertainties surrounding this assumption and the inconsistencies introduced by past practice. Further attempts to make use of long-term erosion plot data in validating and developing empirical calibration relationships (cf. Elliott *et al.*, 1990; McIntyre *et al.*, 1991) and to refine theoretical accounting procedures (cf. Quine, 1989), for example by incorporating the size selectivity of erosion and deposition processes, are undoubtedly required. Nevertheless, with the exercise of care and critical appraisal, the calibration problem should not be seen as a major impediment to the wider application of the caesium-137 technique. The authors have favoured the application of theoretical accounting procedures, which represent the aggregate effect of all redistribution processes operating over the period since the initiation of atmospheric fallout to establish site-specific calibration relationships (cf. Walling & Quine, 1990).

The preceding discussion has outlined the theoretical and empirical evidence to support the fundamental assumptions of the caesium-137 technique. The validity of these assumptions is implicit in the remainder of the paper which discusses potential applications. In essence the technique as discussed involves establishing the local baseline or reference inventory by sampling uneroded undisturbed locations, and identifying the extent of erosion or deposition at other sampling points by comparing their inventory values with the reference and applying a calibration relationship.

SOME POTENTIAL APPLICATIONS OF THE CAESIUM-137 TECHNIQUE

The field scale: detailed surveys

Having established the local caesium-137 reference inventory and a calibration procedure for relating the proportion of the inventory gained or lost at a particular sampling point to the erosion / aggradation rate, each measurement of caesium-137 inventory from a sampled field can

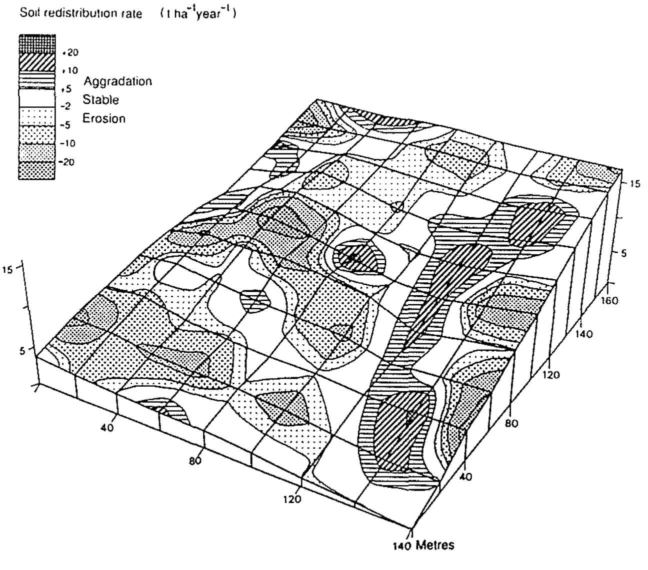

FIG. 4 The pattern of erosion and aggradation established for a field at Fishpool Farm, Gwent, UK, using caesium-137 measurements.

provide a medium-term (*ca.* 35 year) retrospective estimate of the soil redistribution rate. It is therefore possible to investigate the pattern of soil redistribution across a field at a level of detail that would be effectively impossible using any other approach. For example, a 20 or 25m grid of sample collection sites has been used in the investigation of 13 fields on a range of soil types in the UK (Quine & Walling, 1991; Walling & Quine, 1991). The pattern of soil redistribution for one of these fields, on a silty-clay soil at Fishpool Farm in Gwent (51.8N 2.8W) is illustrated in Fig. 4. Data of this spatial resolution are uniquely suited to the investigation of topographic controls upon erosion and deposition (Quine & Walling, 1992).

Where the topography is less complex, it is possible to identify spatial patterns of soil redistribution using lower sampling densities. Figure 5 portrays the pattern of erosion and aggradation for a field near Ha Sofonia, Lesotho (29.3S 27.6E). This was achieved using a series of five parallel transects, with 20 m sample spacing, aligned down the local slope. Despite the lower spatial resolution, it is still possible to identify the topographically related pattern of erosion on the steep side slopes and deposition at the base of the field.

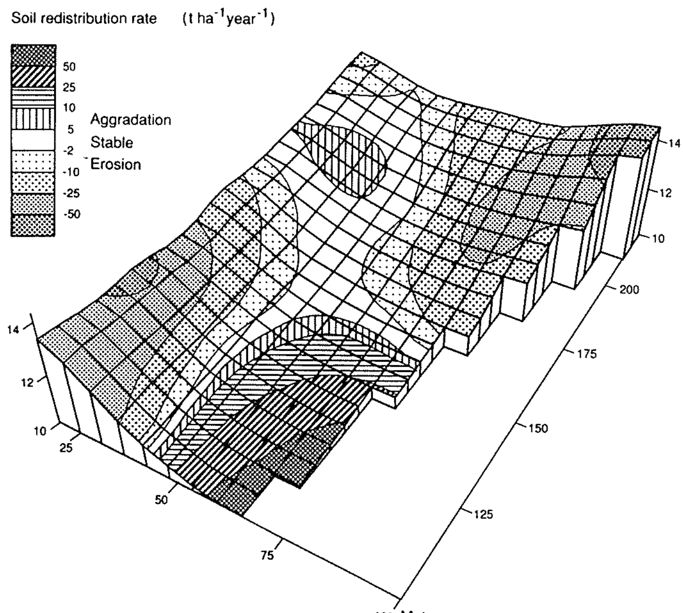

FIG. 5 The pattern of erosion and aggradation established for a field near Ha Sofonia, Lesotho, using caesium-137 measurements.

In addition to providing a visual impression of the pattern of soil redistribution rates, the point data may also be integrated to provide a range of measures of erosion and aggradation. These measures of redistribution for the fields depicted in Figs. 4 & 5 are listed in Table 1.

The measurement of both gross and mean erosion rates allows an assessment of the true severity and potential on-site impact of erosion within the area under examination. Furthermore, the assessment of both net soil loss and the sediment delivery ratio permits evaluation of the off-site threat posed by sediment leaving the field. It is essentially impossible to obtain such data by any other means.

TABLE 1 Integrated field data for the fields at Fishpool Farm, UK and Ha Sofonia, Lesotho illustrated in Figs. 4 and 5.

Measure	Fishpool Farm	Ha Sofonia
Gross erosion rate (t ha^{-1} $year^{-1}$)	5.1	13.5
Eroding sites		
Mean erosion rate	8.1	20. 5
% total area	64	66
% area eroding with rate >		
2 t ha^{-1} $year^{-1}$	47	60
4 t ha^{-1} $year^{-1}$	34	54
Aggrading sites		
Mean rate (t ha^{-1} $year^{-1}$)	8.9	17.5
% total area	36	34
Net erosion rate (t ha^{-1} $year^{-1}$)	1.9	7.8
Sediment delivery ratio (%)	37	58

The basin scale: reconnaissance surveys

The development of effective soil conservation and land management strategies is dependent upon both detailed field-scale studies, and more extensive basin-scale data. Whilst the latter could be obtained by undertaking detailed studies of contiguous fields (cf. Walling & Bradley, 1988), this will rarely be feasible because of resource constraints. It is therefore important to develop strategies for using caesium-137 measurements in reconnaissance surveys. In practice these will involve the collection of small numbers of representative samples which can be used to characterize the erosion rates of specific fields or areas or the use of a small number of measurements to provide 'ground truth' for extrapolation procedures.

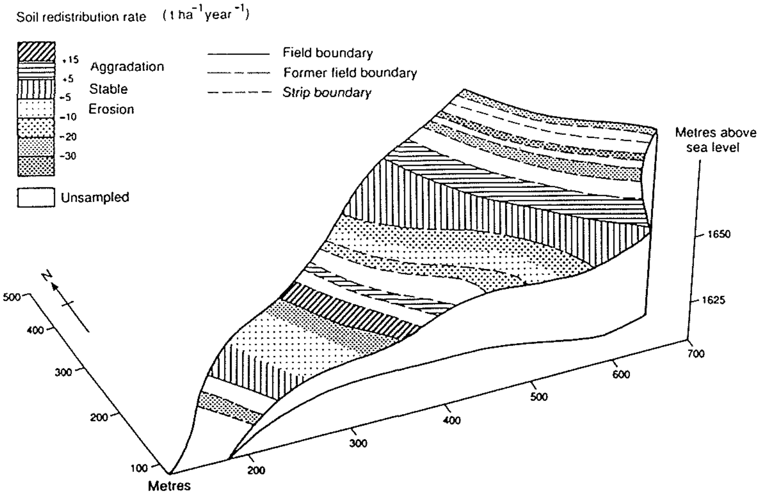

FIG. 6 Rates of net soil erosion and aggradation derived using caesium-137 measurements for contour strips along a slope transect near Ha Sofonia, Lesotho.

This approach was employed in Lesotho to investigate erosion from cultivated land at the basin scale. Here, the cultivated land occupies slope-foot and valley-floor locations and many of the fields have been divided into strips by buffers following the line of the contours. Five to ten soil cores were collected from each of a selection of representative contour strips, thereby providing estimates of net erosion from the individual strips (Fig. 6). The strip data may be combined to produce field-based estimates and the potential for extrapolating these field-based estimates to adjacent areas has been investigated using the following procedure:

(a) The four sampled fields were assigned to one of three erosion classes (0-5, 5-10, >10 t ha^{-1} $year^{-1}$) on the basis of the combined strip data.

(b) Field reconnaissance indicated that the major topographic controls upon erosion at the Lesotho site were likely to be slope angle and slope length (expressed as both field and strip length). These data were assembled for the sampled fields and for six other transects in the same catchment representative of several additional blocks of fields.

(c) The topographic variables (field length, field slope angle and strip length) were used to classify the study fields using cluster analysis. This classification produced three groups of fields, each containing at least one field from the sampled transects.

(d) Each group was assigned to the erosion class of the sampled field which it contained. One group contained two fields from the sampled transect, both of which had been assigned to the same erosion class.

(e) Verification of classification by comparison with erosion rates estimated from caesium-137 measurements for four additional fields on the extrapolated transects.

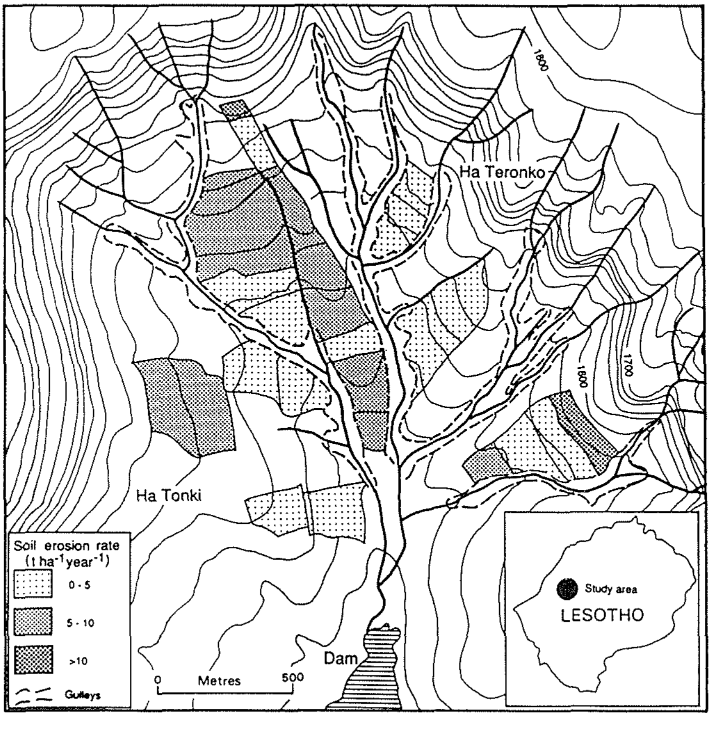

FIG. 7A reconnaissance survey of net erosion rates on cultivated fields near Ha Sofonia, Lesotho.

The results of the classification and extrapolation are illustrated in Fig. 7. Although the classification must be viewed as tentative because of the small number of fields sampled, its internal consistency and the verification provided by the additional samples suggest that this approach to the use of caesium-137 data in reconnaissance level studies has considerable potential. Several procedures for producing erosion hazard maps based on topographic and other land use and environmental variables have been documented in the literature (cf. Stocking *et al*, 1988). However, such procedures generally lack the ability to assign quantitative estimates of erosion rates to the mapped classes. Caesium-137 measurements provide a means of assembling the required 'ground truth' data and the mapping procedures can in turn be viewed as providing the basis for extrapolating a suite of representative caesium-137 measurements.

THE PROSPECT

The caesium-137 technique has been successfully used for soil erosion investigations in North America, Australia and Europe. Until recently applications have been much rarer in developing countries, where soil erosion frequently poses a more serious threat. Nevertheless, the viability and potential of the caesium-137 technique in areas outside the temperate zone has been demonstrated by the results presented here and by the recent work reported by Menzel *et al.* (1987) and Zhang *et al.* (1990). The full potential of the caesium-137 technique will, however, only be realised with the development of sampling and extrapolation strategies which permit the assessment of erosion over wide areas. The approach described here and the use of landform classification in extrapolation by Martz & de Jong (1991) represent the first stages in exploiting the reconnaissance potential of the caesium-137 technique. Further improvement of these methodologies and their integration with GIS and satellite imagery could transform the technique from a powerful geomorpholgical tool used primarily for detailed studies of small areas to one that is applicable to wider areas and is capable of providing a source of valuable data for land management.

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