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The identification and quantification of sediment sources using ^{137}Cs

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ABSTRACT The environmental radioactive tracer ^{137}Cs was used to indicate sources of soil erosion in a small drainage basin in the Hunter Valley, New South Wales, Australia. At sites undergoing little or no erosion, the ^{137}Cs had accumulated in the upper soil profile and eroded soils contained relatively less ^{137}Cs. Cultivated soils were identified as the chief sediment source, since they contained, on average, only one-third the ^{137}Cs of soils under grass cover. While the calibration of the ^{137}Cs technique to quantify soil loss remained uncertain, ^{137}Cs concentrations did appear to be related to some degree to a soil aggregate stability index.

INTRODUCTION

Within the drainage basin system identification of sediment sources may be relatively easy, but their quantification may be more difficult. Furthermore, the temporary storage of sediments on slopes and flood plains further complicates the interpretation of sediment load data at the drainage basin outlet. Recently, tracer concepts have been applied to the identification of sediment sources, including the use of magnetic properties (Walling *et al.*, 1979) and radioactivity (Ritchie & McHenry, 1975). The environmental tracer caesium-137 (^{137}Cs), half-life 30 years, has also been used to determine sedimentation rates in lakes, alluvial fans, flood plains and reservoirs (Ashley & Moritz, 1979; Loughran *et al.*, 1981; Ritchie *et al.*, 1975; Campbell & Ross, 1980).

This paper reports the use of the tracer ^{137}Cs in identifying surficial sources of soil erosion in a small drainage basin in the Hunter Valley, New South Wales, Australia. Its possible use in quantifying the rate of sediment delivery in relation to land use and a soil aggregate stability index was also investigated.

STUDY AREA

The drainage basin selected for study, Maluna Creek (1.7 km^2), is located approximately 50 km inland from Newcastle (32°48'S;

151°16'E). It has steep, forested slopes in its upper reaches (60% of the basin area), and downstream hillslopes under viticulture (10%) or pasture (30%). Mean annual rainfall is approximately 750 mm and relief ranges from 480 to 140 m. Brown podzolic soils, lithosols and coarse textured earths are dominant on the steeper slopes, with black and brown earths, brown podzolic soils and non-humic skeletal soils under grassland and vines.

During the year April 1976-March 1977 concentrations of suspended sediment in Maluna Creek were higher than in a neighbouring stream draining grassland and forest, and were attributed to cultivation activities (Geary, 1981). At a gauging station immediately downstream from Maluna (basin area 4.9 km^2) the suspended sediment transport rate was 149 t $km^{-2} year^{-1}$ (Geary, 1981).

Soil losses from runoff-erosion plots (2 m^2 in area) indicate that a bare soil surface can contribute in excess of 13 times more sediment than plots with either grass or sclerophyll forest cover, even though runoff rates may be comparable (Table 1). Water samples taken during storm runoff events can have sediment concentrations in excess of 105 000 mg l^{-1} in the cultivated vineyards, compared with concentrations of 27-333 mg l^{-1} in runoff from grassland and forest (Table 2).

TABLE 1 Runoff and soil loss from plots, 18 September 1978 to 17 September 1980, Maluna Creek basin

Plot	*Ground cover*	*Rainfall (mm)*	*Depth of runoff (mm)*	*% Rainfall to runoff*	*Soil loss (g)*
A	*Forest*	*1138*	*1*	*0.1*	*5*
B	*Leaf litter*	*1106*	*29*	*2.6*	*26*
C	*Grass*	*1215*	*37*	*3.1*	*77*
D	*Grass*	*1165*	*98*	*8.4*	*136*
E	*Bare soil*	*1177*	*101*	*8.6*	*1813*

Plot area: 2 m^2

TABLE 2 Sediment content of runoff water in the Maluna Creek basin

	Sediment content ($g\ l^{-1}$)			
(a) BARE SOIL SURFACES				
Unsealed road gutters	*4.98;*	*8.03;*	*14.91*	
Cultivated vineyard	*1.20;*	*105.70;*	*44.15;*	*34.27*
(b) VEGETATED SURFACES				
Grass and bare rock	*0.19*			
Forest	*0.33;*	*0.03*		
Creek from grassland catchment	*0.04;*	*0.05*		

The investigation reported here contrasts the contributions of some of these sediment sources using the environmental tracer ^{137}Cs.

BACKGROUND AND METHOD

Caesium-137 is a fallout product of atmospheric nuclear weapons' testing, and there is no other natural source for this isotope. The isotope reaches the earth's surface dissolved in rainfall and, once in contact with the soil, becomes firmly adsorbed onto soil fines. Sites undergoing little or no erosion usually exhibit their highest concentrations of ^{137}Cs within the upper 5 cm. The levels of ^{137}Cs at such sites may closely represent the total input of ^{137}Cs to the drainage basin. If the soil's upper layers have been eroded progressively, thereby preventing build-up of ^{137}Cs, the relative levels of the tracer in the soil profile should indicate the degree of erosion. The use of ^{137}Cs in geomorphological research has been reviewed by Wise (1980).

A first survey of ^{137}Cs distribution in the Maluna Creek basin was carried out at 11 sites on hilltops and hillslopes under forest, grass and vines (Campbell *et al.*, in press). At each site, samples were obtained for depth increments of 1, 2 or 3 cm, yielding a total of 77 samples for ^{137}Cs analysis. At three sites under forest, ^{137}Cs concentrations (per unit depth and adjusted for silt plus clay content) averaged 33.3 mBq $g^{-1}cm^{-1}$. Samples from four sites under grass cover revealed no apparent distinction between hilltop and hillslope positions, and ^{137}Cs concentrations averaged 16.3 mBq $g^{-1}cm^{-1}$. Cultivated soils in four locations had ^{137}Cs concentrations ranging from 5.7 to 4.0 mBq $g^{-1}cm^{-1}$ (average 4.7). Uncultivated soils had ^{137}Cs concentrated in the upper 8 cm whereas in the cultivated vineyards ^{137}Cs was relatively evenly distributed in the ploughed layer, estimated to be about 15 cm deep on average. On the basis of these results, a rather more extensive survey seemed warranted to determine ^{137}Cs levels and, therefore, estimates of soil loss. This took the form of comparisons between grass covered and cultivated vineyard sites for soils within the same soil mapping unit (Loughran *et al.*, 1981).

In previous soil erosion studies employing the ^{137}Cs technique, several samples were taken to estimate ^{137}Cs content for a single core (Ritchie *et al.*, 1974; McHenry & Ritchie, 1977; McCallan *et al.*, 1980). To reduce the number of laboratory analyses, a single-core technique was employed in Maluna basin. A further 17 sites were selected for ^{137}Cs sampling by core, five on grassed hilltops and slopes, the remaining 12 under vines. Soil sampling was carried out in March and April, 1981. Within each soil mapping unit, at least one site under grass cover was sampled. Hilltop sites were selected where possible (Table 3: CS4, CS13 and CS16), otherwise spur tops at a lower altitude were used (Table 3: CS2 and CS5). These sites were considered representative of the particular soil groups under grass and there was no evidence of surface erosion.

The complex micro-topography of the vineyards made any form of systematic sampling difficult. The "ridge and furrow" cultivation method, the grass covered absorption banks to trap runoff and eroded soil, the unequal row and block length and the varied general

TABLE 3 Caesium-137 content of soil-core samples

Soil mapping unit	Sample no.	Bulk density (g cm^{-3})	% Silt + clay	^{137}Cs in sample (mBq)	^{137}Cs conc. in soil (mBq g^{-1})	^{137}Cs conc. in silt + clay (mBq g^{-1})
CULTIVATED SOILS (under vines)						
V	CS1	1.38	54	3644	2.6 ± 0.8	4.8
G	CS3	1.28	70	2132	1.5 ± 0.7	2.1
G	CS9	1.17	73	4637	3.3 ± 0.9	4.5
G	CS10	1.05	72	1370	1.1 ± 0.7	1.5
G	CS11	0.99	70	3316	2.9 ± 0.8	4.1
G	CS12	0.98	71	3212	3.0 ± 0.8	4.2
D	CS6	1.34	49	1363	0.9 ± 0.8	1.8
D	CS7	1.34	53	2602	1.9 ± 0.7	3.6
D	CS8	1.38	42	7322	4.8 ± 0.8	11.4
D	CS17	1.22	37	5326	4.2 ± 0.7	11.4
I	CS14	1.10	82	3527	2.6 ± 0.5	3.2
I	CS15	1.04	64	4488	3.6 ± 0.6	5.6
UNCULTIVATED SOILS (grass cover)						
V	CS2	1.44	30	7127	4.1 ± 0.5	13.7
G	CS4	1.21	87	8643	5.7 ± 0.7	6.6
G	CS16	1.21	72	7774	5.1 ± 0.6	7.1
D	CS5	1.21	61	8731	7.7 ± 1.0	12.6
I	CS13	1.20	79	9346	6.3 ± 0.6	8.0

NOTE: Soil mapping unit V: Lithosol/yellow podzolic soil (Uc 2.12/ Dy 4.41/Dy 2.41: Northcote Class: Northcote, 1971). G: Black earth (Ug 5.32/Ug 5.12/Ug 5.22). D: Brown earth (Um 6.21). I: Brown podzolic soil/chernozem (Dn 1.11/Uf 5.21).

topographic slopes provide an environment of almost infinite variety. Within the group of cultivated soils, therefore, several site-types were sampled in order to achieve a composite impression of ^{137}Cs levels.

One sample (CS1) on soil mapping unit V (lithosol/yellow podzolic soil) was taken at the centre of a row in the middle of the block of vines. Cultivated soils of mapping unit G (black earth) were sampled close to a north-facing hilltop (CS3), on a south-facing slope in the centre of a block (CS9), and on a north-facing slope in a downslope sequence CS12, CS11 and CS10 (spaced at 20 row intervals and 20 m along the row). Samples at intervals of 10 m along a single row between vines were obtained for soil mapping unit D (brown earth) (CS6, CS7 and CS8). The last of these three was resampled one month later (CS17). At 5 and 15 rows downslope, soil mapping unit 1 (brown podzolic soil/chernozem) was sampled, CS14 and CS15 respectively.

Since the previous study (Campbell *et al.*, in press) had shown ^{137}Cs to be concentrated in the top 12-15 cm of the soil, a corer, 15.2 cm deep and 10.7 cm inner diameter, was used for sampling. The corer, with a bevelled lower edge, was tapped into the soil until flush with the surface. After excavation, a thin steel plate was used to slice the sample level with the lower surface of the cylinder. The samples were oven dried and weighed so that bulk density could be estimated. Before analysis for ^{137}Cs, stones were removed from the sample by sieving (2400 μm). Caesium-137 activity was determined by gamma-spectroscopy using a germanium (Li) detector and expressed as total activity in millibecquerels (mBq) and concentration (mBq g^{-1}). (The becquerel is the SI unit of activity and represents one nuclear transformation per second). Since the ^{137}Cs is preferentially adsorbed onto fine sediments, concentrations were also expressed per unit silt plus clay in the sample (USDA standard: <0.05 mm).

It was hypothesized that ^{137}Cs concentrations should be lower in the cultivated soils because of their increased susceptibility to erosion due to cultivation, compared with soils under grass cover.

RESULTS

Core samples from 17 sites, representing four different soil mapping units, were analysed for ^{137}Cs content. The data are shown in Table 3. Bulk density measurements are considered approximate due to the difficulty of setting the upper datum of the core with the ground surface. Recently ploughed soils showed the lowest values, as was expected. For the cultivated soils, ^{137}Cs concentrations range between 0.9 and 4.8 mBq g^{-1} and uncultivated 4.1 to 7.7 mBq g^{-1} (Table 3). Within each soil mapping unit, samples from cultivated soils have lower ^{137}Cs concentrations than their uncultivated counterparts (Table 3).

DISCUSSION

Caesium-137 levels for the two sample groups, cultivated and uncultivated, are significantly different at the 0.001 level for the Mann-Whitney U-test (Siegel, 1956), whether expressed as concentration per unit silt plus clay, concentration per unit weight or total ^{137}Cs content per core. This difference may be due to several factors, including sampling method, loss of ^{137}Cs in crops from the cultivated vineyard, direct loss of the isotope in runoff before adsorption onto particles, and soil erosion.

Sampling method

The determination of total ^{137}Cs content in samples from uncultivated soils has probably been unaffected by the sampling method, since the depth profile analyses undertaken elsewhere in the Maluna drainage basin showed ^{137}Cs to be concentrated in the upper 8 cm, well within the 15 cm range of the core. At cultivated sites, significant ^{137}Cs was sometimes found below 15 cm, but since these amounts were quite small, underestimation was probably only of the order of 20% at the most.

Caesium-137 concentrations in core samples are not strictly comparable, since a depth of 15 cm of uncultivated soil is not equivalent to 15 cm depth of cultivated soil, although differences in sample weight have been accounted for in the calculation. It is, therefore, likely that a greater amount of weakly labelled soil has been included in cores from uncultivated sites and thus diluted ^{137}Cs concentrations.

The effects of preferential adsorption of ^{137}Cs onto soil fines can be allowed for by expressing concentrations per unit silt plus clay content of the sample (Ritchie *et al.*, 1975). Very probably, this is the most satisfactory measure for comparison of cores in this study.

Loss of ^{137}Cs in cultivated crops

The harvest of grapes and the annual pruning of vines may also remove ^{137}Cs from the cultivated parts of the basin in the unlikely event that the isotope has entered the "vegetation store" (Wise, 1980). However, samples of grapes and vine prunings were found to have no ^{137}Cs within them.

Loss of ^{137}Cs in runoff and deep infiltration

Adsorption of ^{137}Cs onto soil particles from precipitation, although not instantaneous, is rapid (Kaufman *et al.*, 1955). Runoff of surface water during rainstorms may well have the effect of reducing the amount of ^{137}Cs available for adsorption, and since runoff rates and pathways can be complex and variable, it is difficult to make allowances relative to the two land use types under consideration. Nevertheless, the loss of ^{137}Cs in runoff water can be considered minimal.

The black earth and chernozem soils of Maluna Creek basin can exhibit dessication cracks after prolonged drought. Under such circumstances, rainfall and ^{137}Cs could infiltrate deeply, labelling lower soil layers out of reach of the core sampler. Of the cultivated soils, soil mapping unit G (black earth), does have the lowest ^{137}Cs concentration with respect to silt plus clay content (Table 3).

Soil erosion

The observed differences in ^{137}Cs content between cultivated and uncultivated sites are probably chiefly due to more effective raindrop splash, runoff erosion and rain-flow transportation (Moss *et al.*, 1979) on exposed soils. These erosion processes can be very selective. In the vineyards, soil ridges tend to transmit water and eroded sediment to the end of rows and thence to waterways that run downslope between blocks of vines. During severe storms, soil ridges can become dissected, and runoff and sediment routed more directly. Sediment fans build up at the slope base. Subsequent ploughing and the return-carting of soil upslope will tend to smooth out localized losses and gains of soil and adsorbed ^{137}Cs. Superimposed on this system of soil movement, ploughing between rows to maintain soil ridges will gradually work soil downslope.

The accurate calibration of the method remains an obstacle to its use in quantifying soil losses. No comparative soil erosion data are available for the Maluna basin for the period 1954-1981. The vineyards were planted in 1970 and existing research records date back to only 1978. Alternatively, a comparison of the ^{137}Cs content of the soil against an index of soil erodibility or soil loss calculated from the Universal Soil Loss Equation, as undertaken by Ritchie *et al.* (1974), may prove fruitful. The ^{137}Cs concentrations of soil cores from the Maluna basin have been correlated with an index of soil aggregate stability (Collis-George & Figueroa, personal communication, 1980) and the resultant plot is shown in Fig.1. The index is defined as A/B, where A is the volume of water drained from a sample of soil aggregates of size range 1-2 mm (excluding shrinkage) from zero to approximately -60 cm matric potential, divided by the most common moisture potential at which drainage occurred. B refers to the same quantities for a sand fraction of the same size range as the soil aggregates before test. The greater the index value, the more stable and potentially resistant to transport the aggregate is. While not statistically significant, the trend of the relationship between ^{137}Cs concentration and the index suggests that ^{137}Cs levels are lowest in less stable soils.

CONCLUSIONS

Core sampling of soils for ^{137}Cs on grass covered and cultivated

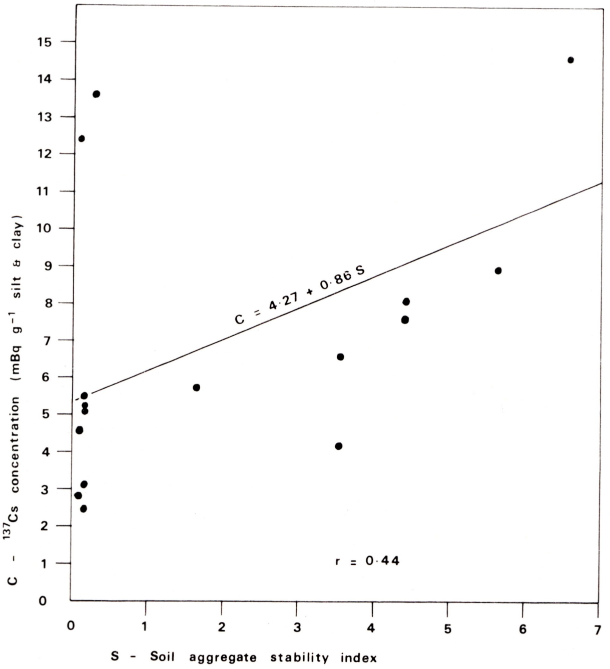

FIG.1 The relationship between the soil aggregate stability index and ^{137}Cs concentration for core samples CS1-CS16.

slopes confirms the results of an earlier survey in the basin (Campbell *et al.*, in press). Caesium-137 levels are, on average, two to three times lower under cultivation. Runoff plot data and runoff sampling (Tables 1 and 2) identify the cultivated soils as a major sediment source. Therefore, the ^{137}Cs technique adequately indicates the areas of most serious soil loss. Obviously, further research into the relationship between the ^{137}Cs content of soils and their potential erodibility and aggregate stability is warranted.

The effectiveness of the technique has yet to be demonstrated for studies of stream bed and bank erosion, soil tunnelling and gullying, all of which contribute to suspended sediment loads of streams. More conventional survey-type methods are, however, probably adequate for estimating contributions from these sources. It is the more insidious surficial erosion of slopes that often defies identification in the field. While the ^{137}Cs technique may not yet be capable of quantifying these soil losses, this study demonstrates that it can be used to identify and rank sediment sources on slopes in Maluna Creek drainage basin.

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