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Measuring soil movement using ^{137}Cs: implications of reference site variability

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Abstract To determine soil movement based on redistribution of ^{137}Cs, 50 samples were taken at grid points on a 1 ha hillslope plot. There was a correlation between slope position and areal concentration of ^{137}Cs, suggesting that soil had been moved from upslope areas and deposited in lower slope positions. However, detailed sampling was also undertaken at eight suitable nearby reference locations to determine ^{137}Cs fallout over the region. The variability in areal concentrations at these locations was approximately equal to the variability observed in the test plot, thus suggesting that fallout variability could account for the observed differences in ^{137}Cs areal concentration. Therefore it cannot be concluded that the ^{137}Cs distribution reflects only soil transport. At least part of the ^{137}Cs distribution could result directly from the pattern generated by fallout and immediate runoff. A method to reduce the variability resulting from fallout and distribution processes using the ratio of ^{210}Pb$_{ex}$ to ^{137}Cs is suggested.

INTRODUCTION

The fallout radionuclide ^{137}Cs has been used extensively to quantify patterns of soil accumulation and movement within landscapes (Campbell *et al.*, 1982; Loughran *et al.*, 1990; McCallan *et al.*, 1980; Quine & Walling, 1991). The technique involves measuring the total input of ^{137}Cs at a "reference" area and then comparing it to values observed from disturbed locations. Areas with lower areal concentrations than the reference value are considered to have undergone erosion and those with higher concentrations have experienced soil accumulation. Reviews of this technique are given in Ritchie & McHenry (1990) and Sutherland (1991).

A central assumption of this technique is that local fallout is uniformly distributed (Walling & Quine, 1992). However this assumption has rarely been tested (see Fredericks *et al.*, 1988; and Sutherland, 1994) and often little consideration is given to the inherent natural variability of ^{137}Cs in undisturbed "reference" areas.

In this study, ^{137}Cs areal concentrations have been measured over a 1 ha hillslope plot. The variability in the ^{137}Cs concentrations are first interpreted in terms of soil redistribution, assuming a uniform ^{137}Cs deposition. The variability of ^{137}Cs concentrations are then assessed by examining ^{137}Cs concentrations at eight adjacent sites which fulfil the "reference site" criteria used by others (Ritchie *et al.*, 1974; McCallan *et al.*, 1980; Campbell *et al.*, 1982). These data are then used to determine whether or not the variability in ^{137}Cs concentrations at the 1 ha hillslope site could be explained in terms of fallout variability.

A method of reducing the variability of ^{137}Cs due to fallout effects, utilizing the covariability of excess ^{210}Pb (^{210}Pb$_{ex}$) over its parent ^{226}Ra, is then suggested.

SITE DESCRIPTIONS

The experimental work was undertaken in Canberra within the Australian Capital Territory (34°S, see Fig. 1) and at St Helens, Tasmania (latitude 42°S). The long term average rainfall in Canberra is about 630 mm which falls evenly across the city, annual deviations from this can be up to 100 mm. The one hectare test plot was at Yarramundi Reach on the western shores of Lake Burley Griffin which lies centrally within the city. The maximum vertical relief at the site was about 5 m. Adjacent to this plot, approximately 50 m distant, is a commercial *Pinus radiata* plantation. Based on data presented by Longmore *et al.* (1983) for Brisbane, the net fallout of ^{137}Cs in Canberra is expected to be about 640 Bq m^{-2} corrected to 1991, although this makes no allowance for the 10° latitude difference between them.

Eight other locations were chosen (Fig. 1) which fitted the requirements for ^{137}Cs reference locations, that is (a) they had been undisturbed and stable for at least 35 years and (b) soil movement was considered unlikely. The sites at Black Mountain reserve, Haig Park, Bugden Avenue Park, Narrabundah and Collins Park had a uniform

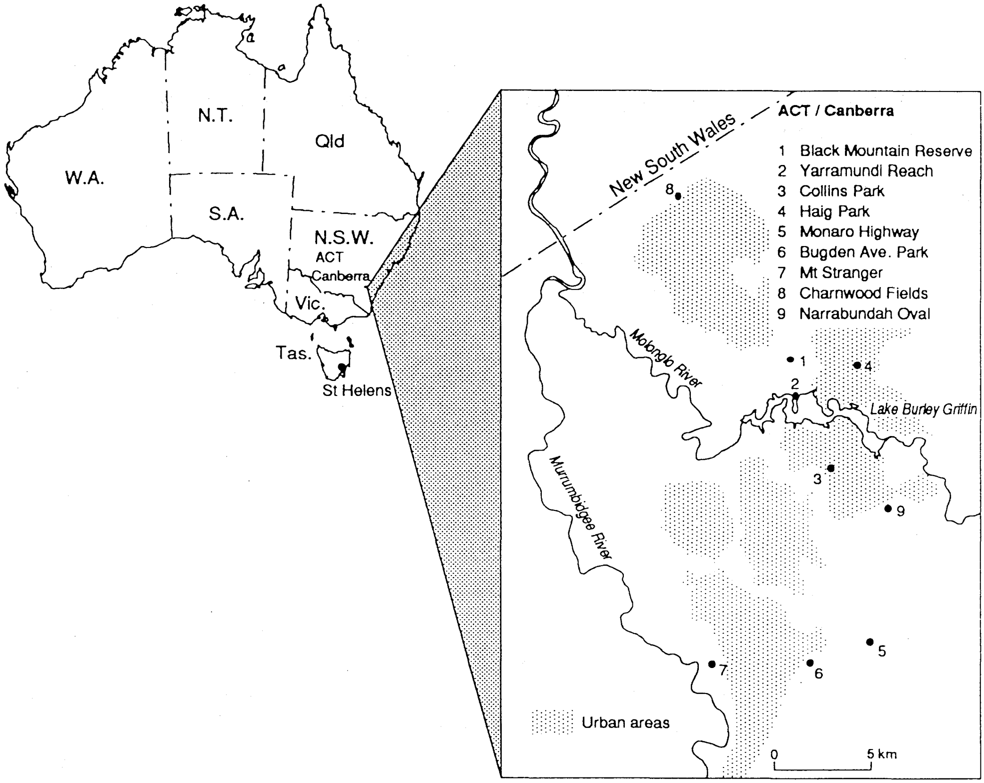

Fig. 1 Location diagram of Yarramundi Reach test plot and eight reference sites sampled within the ACT, Australia.

overstorey species of either Eucalyptus, Poplar, Pinus or mixed deciduous trees of European origin. The average distance between individuals in these locations was about 10-20 m. The sites at Charnwood, Mt Stranger Reserve and Monaro Highway had no tree cover, although there was a persistent cover of a mix of native grasses and sedges. All the reference locations were uniform over at least 3 ha, and were chosen to be independent of factors such as aspect and slope position. The surface slope was less than 10° at all these locations.

The St Helens forest (latitude 42°S) is dry sclerophyll and consists predominantly of *Eucalyptus seberii*. The understorey is largely nonexistent due to frequent burning. The average distance between individual trees is about 20 m. This overstorey and landform type is persistent over an area of about 100 ha. The soils here are described as yellow podzolics which have been formed on adamellite granites and are classified as Uc2.21 (Northcote, 1979) (W. Nielson, 1994, personal communication). All the measured plots had slopes less than 15°.

SOIL SAMPLING AND ANALYSIS

Yarramundi Reach

An area of 100 × 100 m was divided into a 10 × 10 m grid. A series of 50 samples were taken for ^{137}Cs analysis from within every second cell. These were obtained by hammering a 20 × 20 cm frame into the ground and excavating the soil within this area to a depth of 25 cm. This produced a mass of soil in the range 8-12 kg, depending on soil density. A detailed topographical survey was then undertaken of this site with vertical resolution of about 1 cm.

Reference sites

At each of the reference sites 9 samples were taken by the method described above for Yarramundi Reach except for Black Mountain where 5 samples were taken. At the Narrabundah, Monaro, Bugden Avenue and Black Mountain locations all the samples were analysed separately. At Charnwood, Haig Park, Collins Park and Mt Stranger Reserve the nine samples were randomly bulked into groups of three which were then analysed.

St Helens

At St Helens 20 representative soil cores, each of surface area 78 cm^2, were taken from two reference plots, representing a surface area of about 800 m^2. The cores were 300 mm deep and contained approximately 2500 g of soil. Upon returning to the laboratory the tubes were cut into two sections (0-5, 5-30 cm) which were measured independently to allow for greater precision in ^{210}Pb excess concentrations. ^{210}Pb fallout is preferentially retained nearer the surface than ^{137}Cs (Wallbrink & Murray, 1993).

The soil samples in each case were thoroughly homogenized and put through a ring grinder, following which 250 g was removed for analysis (Murray *et al.*, 1987).

RESULTS AND DISCUSSION

Yarramundi Reach

A digital elevation model was created for the Yarramundi Reach site using the SURFER^T software package. The ^{137}Cs (Bq m^{-2}) spatial data were also contoured and the resultant *isocaes* surface (Longmore *et al.*, 1983) has been overlayed onto the terrain model (Fig. 2). Concentration of ^{137}Cs ranged from 300 to 1800 Bq m^{-2}, and uncertainties are about 90 Bq m^{-2}.

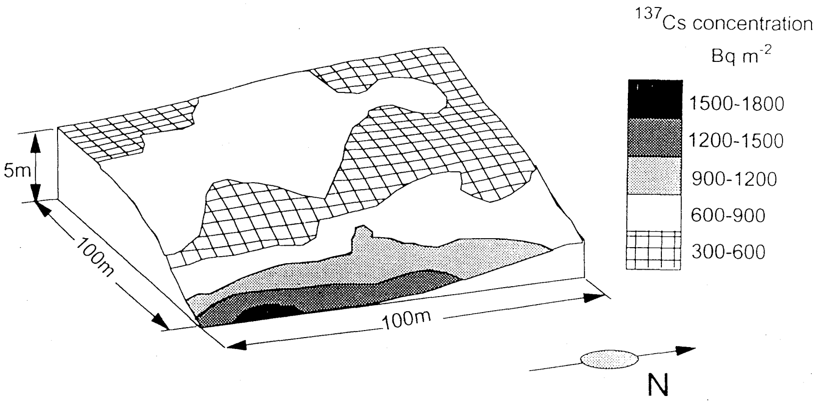

Fig. 2 Map of ^{137}Cs areal concentrations and surface topography over a 1-ha site at Yarramundi Reach, ACT.

The areal concentrations of ^{137}Cs are highest at the bottom of the slope and lowest in the midslope areas. If the Longmore *et al.* (1983) scale of erosivity (converted to Bq m^{-2}, i.e. $<$270 Bq m^{-2} severe erosion, 270-570 moderate erosion, 570-673 mild erosion, 673-860 mild accumulation, 860-1145 moderate accumulation, 1145-1430 heavy accumulation, $>$1430 Bq m^{-2} very heavy) is applied to our site then at least moderate erosion should be observed on the western side of the site and very heavy accumulation of the bottom of the slope.

Physical observation of the site, including examination of stratigraphy in soil pits, revealed no discernible evidence of soil movement or accumulation. There is also a semi permanent soil cover by native grasses which limits soil and particle movement. It is thus considered improbable that soil movement has occurred to the degree suggested by this simple application of Longmore's erosivity scale.

However, rates of soil loss from well managed native pastures, such as at Yarramundi, are known to be in the order of 19 $\pm$ 5 t km^{-2} year^{-1} (R. J. Wasson, personal communication). This is equivalent to a total of about 5.7 $\pm$ 1.5 t of soil in our study area over a 30 year period which calculates to a total average areal soil depth loss of approximately 0.74 $\pm$ 0.2 mm. This represents a total of about 170 kBq, assuming an average ^{137}Cs concentration of 30 Bq kg^{-1} from surface runoff experiments conducted by Wallbrink & Murray (1993). It is assumed that deposition has occurred over the portion of the study area that is greater than 1 standard deviation from the regional average (above the 1050 Bq m^{-2} isoline, representing approximately 10% of the study area). This is equivalent to an addition of 170 $\pm$ 45 Bq m^{-2} over this surface area. This represents a 25% increase over the mean of these ^{137}Cs areal concentrations, and suggests that soil movement may be partly responsible for some of the downslope trend of increasing ^{137}Cs areal activity in this plot.

Possible causes of initial non-uniform distribution of ^{137}Cs

Deposition of ^{137}Cs is known to occur predominantly in association with rainfall. There are two mechanisms that may contribute to a non-uniform distribution of ^{137}Cs at the time of deposition. The first of these is related to attributes of surface topography, which may influence fallout over a scale of one to hundreds of metres. Features such as hills, trees and shrubs affect the random pattern of rainfall by creating persistent perturbations in air flow (Gash, 1986). These perturbations create wind and rain shadows and thus, zones of relative ^{137}Cs depletion and enhancement. In this context the presence of the mature Pinus trees upwind of the Yarramundi plot should be noted. In contrast, concentrations of ^{137}Cs may be increased in the drip zone beneath canopies. The second group of mechanisms which may influence ^{137}Cs deposition are related to soil factors which affect the local movement of rain water on and within the soil over a scale of one to hundreds of centimetres. These include differences in soil density, infiltration capacities and soil chemical properties. The net effects of these processes on ^{137}Cs fallout can be assessed by examining variability of ^{137}Cs at locations that fulfil the reference site criteria.

ACT reference areas

The heterogeneity in ^{137}Cs distribution was estimated by determining the relative standard deviation (*rsd*, also known as coefficient of variation) of ^{137}Cs areal concentrations from a number of soil cores collected from the reference sites within the ACT, where it is thought that no significant soil loss or redistribution has occurred since 1950. The results have been condensed to show the number of samples taken, the average, standard deviations, relative standard deviations and the standard error from each reference location (Table 1). The corresponding values from Yarramundi Reach are also given. The bulked samples from the four sites (noted as * in Table 1) did not represent individual estimates and thus were not included in the calculation of the regional ^{137}Cs variability. This was calculated to be 722 Bq m^{-2} with standard deviation of 305 Bq m^{-2} using data from the other four non-bulked sites (denoted as #). The *rsd* of ^{137}Cs areal concentrations across these reference sites in the ACT was about 42% and compares to 38% at Yarramundi reach. There is a negligible difference in the net regional average if the Yarramundi data are included in the overall reference site average calculations (see Table 1). The ^{137}Cs data also show no systematic difference in average areal concentration between forested or pastured reference sites, with the lowest and highest variabilities occurring in the latter category. The total range of average areal values was from 546 ($\sigma = 98$) Bq m^{-2} at Collins Park to 974 ($\sigma = 356$) Bq m^{-2} at Black Mountain reserve.

The data from all the sites have been plotted (Fig. 3). The mean and standard deviation reference lines (solid and dashed lines respectively) are derived from the non-bulked (black squares) reference site data. It can be seen that bulking of soil samples

Table 1 Yarramundi Reach test plot ^{137}Cs data and values from eight reference sites in the ACT.

Location	Number of samples	Average ^{137}Cs (Bq m^{-2})	Standard deviation (σ)	Relative standard deviation	Standard error
Yarramundi Reach	50	685	272	38	38
Bugden Avenue $^{(F\ \#)}$	9	509	204	40	68
Narrabundah $^{(F\ \#)}$	9	721	159	22	53
Monaro Hwy $^{(P\ \#)}$	9	797	329	41	109
Black Mountain $^{(F\ \#)}$	5	974	356	36	159
Charnwood $^{(P\ *)}$	3 (9)	573			88
Haig Park $^{(F\ *)}$	3 (9)	745			111
Collins Park $^{(F\ *)}$	3 (9)	546			69
Mt Stranger $^{(P\ *)}$	3 (9)	655			32
# sites (excluding Yarramundi Reach)	32	722	305	42	54
# sites (including Yarramundi Reach)	82	699	288	41	32
St Helens					
^{137}Cs concentration	20	810	380	47	90
		^{210}Pb$_{ex}$/^{137}Cs			
^{210}Pb$_{ex}$/^{137}Cs ratio	20	2.2	0.6	27	0.2

Notes: # denotes all soil samples analysed separately.
* denotes soil samples bulked into groups of 3.
F denotes forest cover, P denotes pasture.

(open triangle) reduces the scatter of ^{137}Cs and allows accurate estimates of site averages to be made with fewer analyses, however information on real field variability is obscured. The standard errors from both the bulked and nonbulked reference areas (Table 1) are, as expected approximately equal.

It is also evident that both the areal ^{137}Cs averages and the spread of concentration data from Yarramundi Reach are consistent with those from the reference areas. There is only one point from the Yarramundi reach data set that is beyond 3 standard deviations of the regional average. The similarity of the remaining values forces us to conclude that although there is evidence that soil redistribution is partly responsible for the variability in ^{137}Cs concentrations at Yarramundi, it is difficult to discern this from the inherent variability resulting from fallout.

Using the ^{210}Pb$_{ex}$:^{137}Cs ratio to reduce variability

Fallout ^{210}Pb is also deposited primarily in association with rainfall, and so its deposition is likely to be affected by the same factors as ^{137}Cs. If this is the case, then the ratio of

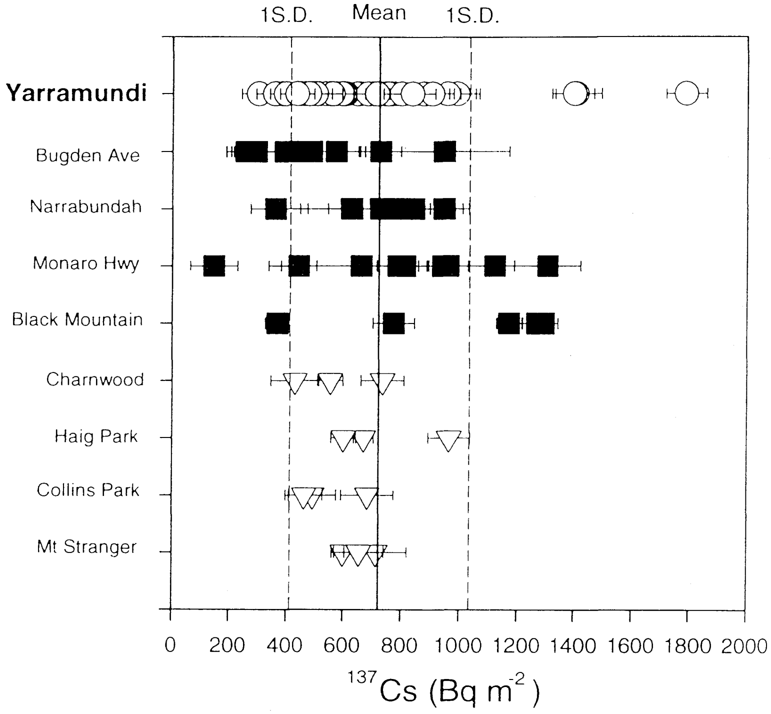

Fig. 3 Spread in ^{137}Cs areal concentration data from ACT reference sites and Yarramundi Reach.

${}^{210}Pb_{ex}$ to ^{137}Cs should be less variable in surface soil than the concentrations of either nuclide alone. This ratio may reduce the variability found at reference sites, and its use has been examined at the St Helens site.

The average ^{137}Cs inventory at St Helens was 810 ($\sigma = 380$) Bq m^{-2} ($n = 20$, see Table 1), with a *rsd* of 47%. The ratio of ${}^{210}Pb_{ex}$ to ^{137}Cs was then determined from the same samples to be 2.2:1 ($\sigma = 0.6$). This is an *rsd* of 27%, which represents a relative reduction in variability of about 40%. Clearly, the ${}^{210}Pb_{ex}/{}^{137}Cs$ ratio is less variable at this site and suggests that it may be a more sensitive indicator of surface soil movement than measurements of ^{137}Cs concentrations alone. The authors are currently pursuing this technique as a means of deriving more stable reference values and are investigating the effect on this ratio of parameters such as particle size, mineralogy and soil chemistry.

CONCLUSIONS

It has been shown that areal concentrations of ^{137}Cs varied with slope position in a 1 ha hillslope plot. Concentrations were highest in the lower areas. A published ^{137}Cs soil erosion relationship suggested that very heavy soil accumulation had occurred in the lower slopes in the last 30 years. However, it was shown that the variability in ^{137}Cs areal concentrations at the site was comparable to the variability in ^{137}Cs fallout determined from nearby uneroded reference sites. This suggests that, at the very least, some of the hillslope site variability could be due to variations in fallout distribution alone.

It is clear that more work needs to be undertaken to identify and quantify the cause of ^{137}Cs variability in the environment. Until this is done, areal concentration measurements of ^{137}Cs should only be used with caution. On the other hand, fallout variability may be reduced by taking the ratio of ^{137}Cs concentration to ^{210}Pb excess. This indicates that the $^{210}\text{Pb}_{ex}/^{137}\text{Cs}$ ratio may be a more reliable indicator of surface soil movement.

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