Sediment movement on hillslopes measured by caesium-137 and erosion pins

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Abstract Caesium-137 results from two grazed hillslopes in southeastern Australia revealed a number of alternating zones of caesium-137 enrichment and depletion. These zones correspond to slope segments where erosion and deposition dominate respectively. Erosion pin results for a logged and burnt hillslope and a log dump at Grafton, New South Wales, over a 19 week period during which two intense storms occurred, also showed alternating zones of erosion and deposition. Sediment movement on grazed and logged hillslopes in southeastern Australia can occur as sediment slugs or pulses over both short (individual events) and medium (40 years) time scales, as well as over distances of metres to tens of metres. These erosional and depositional zones on hillslopes appear to be small scale versions of Pickup's scour-transport-fill sequences.

INTRODUCTION

Soil erosion is a natural process which, in many parts of the world, has been accelerated by human activities, and is causing significant environmental damage (Ritchie & McHenry, 1990). Various methods have been employed to measure soil erosion. Of these methods, the radioisotope ^{137}Cs and erosion pins have been used extensively to quantify soil erosion and sedimentation rates (Haigh, 1977; Loughran, 1989; Ritchie & McHenry, 1990). Caesium-137 is a relatively long-lived radioisotope (half life 30.2 years) produced by atmospheric nuclear weapons testing (with no natural source) that is rapidly and strongly adsorbed by soil particles. Caesium-137 has been present in measurable quantities in soils worldwide since 1954 (Wise, 1980; Longmore, 1982).

Examination of previous ^{137}Cs and slope process studies suggested that sediment moves gradually downslope in a serious of erosional and depositional pulses (Loughran *et al.*, 1989; 1990; Mitchell & Humphreys, 1987; McFarlane *et al.*, 1992). The purpose of this paper is to determine the nature of sediment movement on Australian hillslopes by a combination ^{137}Cs measurements down grazed hillslopes at Monkerai, New South Wales, and Bothwell, Tasmania, and erosion pin measurements on a logged and burnt sandstone hillslope near Grafton, New South Wales (Fig. 1(a)).

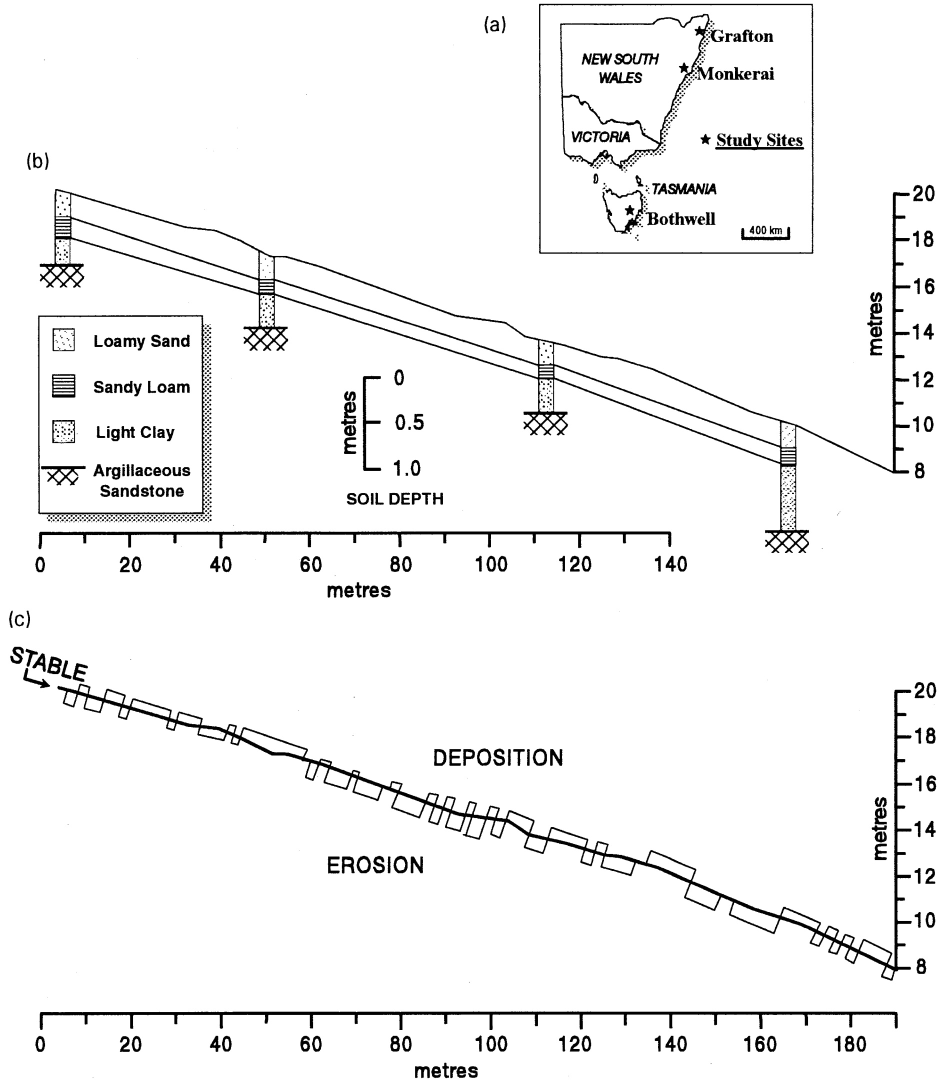

Fig. 1 (a) Location map of study sites. (b) Surveyed slope profile and soil stratigraphy of slope segment used for erosion pin measurements, Grafton. (c) Schematic representation of erosional, depositional and stable zones on the slope segment, Grafton. Erosion and deposition are not plotted to scale.

METHODOLOGY

Caesium-137

The field sampling method for ^{137}Cs was similar to that used by Campbell *et al.* (1988). Reference sites were sampled using a 1000 cm^2 (50 $\times$ 20 cm) steel frame and an adjustable scraper plate. The reference profiles were collected at 2 cm increments to a depth of 12 cm, and were extended to 22 cm by core. An additional five reference cores were collected at Monkerai and four at Bothwell to a depth of 20 cm. The slope samples were collected by a steel cylinder core (20 cm in length). At the two ^{137}Cs study sites, duplicate cores were taken down parallel hillslope profiles, 0.6 m apart and designated transects A and B. At Monkerai, 18 locations were sampled equidistantly down the 360 m long slope on both transects. At Bothwell, 14 locations were sampled equidistantly down the 125 m long slope on both transects. High purity germanium detectors were used to measure the gamma emissions of ^{137}Cs. Corrections were made for the small bismuth-214 peak on the high energy side of the ^{137}Cs peak.

Erosion pins

Erosion pins were installed at 2 m intervals on an 186 m long segment (mean slope angle 3°37′) of a hillslope near Grafton in July 1993, four weeks after the cessation of intensive logging. An 8 m × 20 m grid of pins was also installed on a former log dump on the same slope at the same time that the slope profile was installed. The pins were spaced at 1 m intervals downslope and 2 m intervals across slope. The profile and grid were severely burnt by a wildfire four months after the erosion pins were installed and the pins were remeasured 19 weeks after installation. A metal detector was used to relocate the pins because of frequent burial; 93 of the original 94 pins on the slope profile were found and 94 of the 99 grid pins were relocated undisturbed.

Acid yellow duplex soils are present on the slope (Fig. 1(b)) and ground cover varied between 10 and 75% when the erosion pins were remeasured. Figure 1(b) shows the slope profile and soil stratigraphy, and Fig. 2 shows the erosion grid.

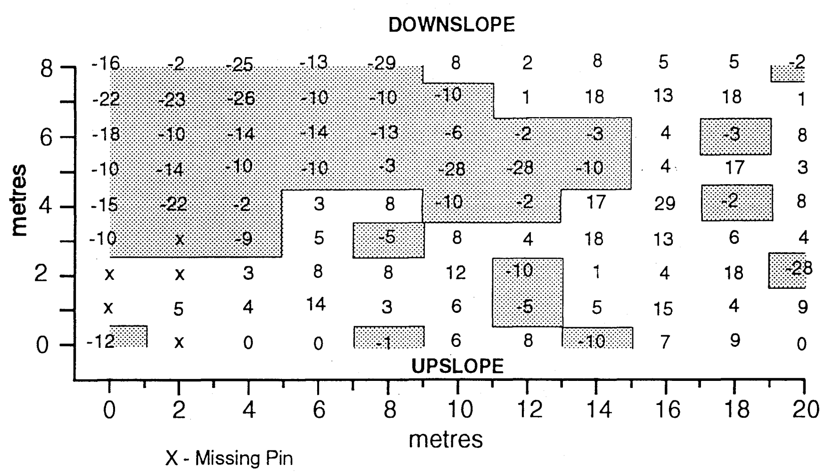

Fig. 2 Soil erosion (mm) at the pin sites for the grid installed on the former log dump, Grafton. Negative sign indicates deposition. The zones of deposition are shown by shading.

Although there were 24 rain days during the erosion pin monitoring period, only one intense storm (31.4 mm in 24 h) occurred between pin installation and the wildfire. A further intense storm (24.5 mm on day 1; 121.8 mm on day 2) occurred between the wildfire and pin remeasurement. The latter event has a return period of 2.9 years on the annual series for 24 h duration, and a return period of 5.0 years for 48 h duration.

RESULTS

Caesium-137

The ^{137}Cs results for both transects at each site are shown in Fig. 3. A weighted reference range was calculated as one standard deviation either side of the reference mean, obtained by averaging the scraper plate and core reference samples. No ^{137}Cs was detected below a depth of 0.14 m at both sites. Sample sites on the hillslope that have ^{137}Cs values within the weighted reference range are considered to be "^{137}Cs stable". A "^{137}Cs stable" site does not necessarily mean that no erosion has occurred, but it may indicate a site where the rate of ^{137}Cs deposition equals that rate of ^{137}Cs loss.

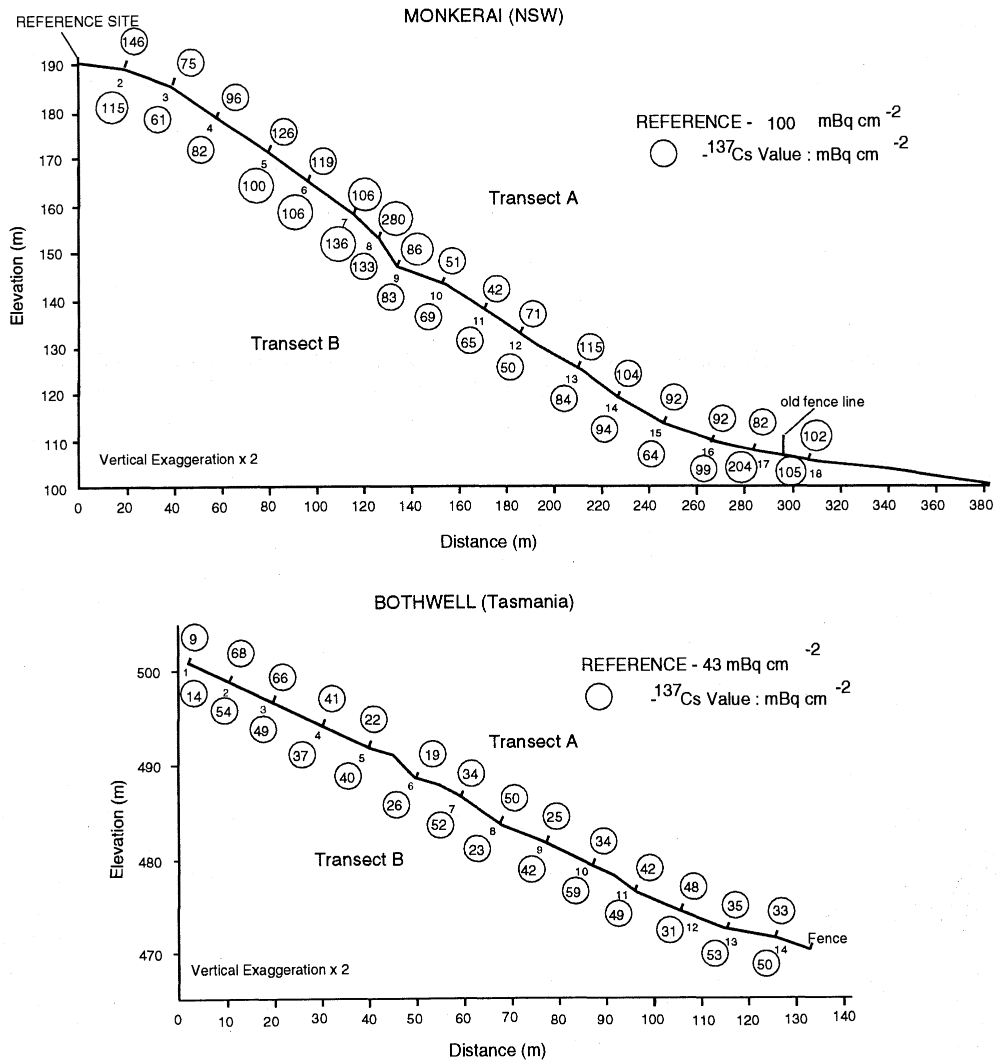

Fig. 3 Caesium-137 distribution on transects: Monkerai (New South Wales) and Bothwell (Tasmania).

The Monkerai site has a ^{137}Cs reference mean of 99.6 ± 3.1 mBq cm^{-2} and therefore a ^{137}Cs-stable reference range of 96.5-102.7 mBq cm^{-2}. The two transects at Monkerai each have 18 sample sites, with ^{137}Cs values varying between 42 and 280 mBq cm^{-2} on transect A, and between 50 and 204 mBq cm^{-2} on transect B (Fig. 2(a)). The average ^{137}Cs values for transect A and B are 105.13 and 97.08 mBq cm^{-2}, respectively. Transect A has one ^{137}Cs-stable site, seven sites with values greater than the reference range and nine below. Transect B has two ^{137}Cs-stable, six sites greater than the reference range and nine below. The highest ^{137}Cs value on transect A is at site 8, which is a deposition zone behind a fallen log. The highest value on transect B is at site 17 at the base of the hill.

The Bothwell site has a weighted reference mean of 43.3 ± 1.6 mBq cm^{-2} and therefore a ^{137}Cs-stable reference range of 41.7-44.9 mBq cm^{-2}. Fourteen sites were sampled, with ^{137}Cs values varying between 9 and 68 mBq cm^{-2} for transect A, and between 14 and 59 mBq cm^{-2} for transect B (Fig. 3). Transect A has four sites that have values greater than the reference range, one ^{137}Cs-stable and nine below. Transect B has seven sites with ^{137}Cs values greater than the reference range, one ^{137}Cs-stable and six below.

Erosion pins

Of the 93 erosion pins on the slope profile, 4.3% exhibited no change, 46.8% erosion and 48.9% deposition. The mean change for the whole profile was −2 ± 13 mm. The negative sign indicates deposition. Time weighting of this value yields an annual rate of −5.5 mm $year^{-1}$. Of the 94 erosion pins on the grid, 3.2% exhibited no change, 50% erosion and 46.8% deposition. The mean change for the whole grid was −1.5 ± 12 mm, again indicating net deposition. Time weighting of this value yields an annual rate of −4.1 mm $year^{-1}$.

Figure 1(c) shows the slope profile with erosion at each pin depicted as a bar (not to scale) below the surveyed profile, deposition as a bar (not to scale) above the profile, and no change as the surveyed profile. Fig. 2 shows the results of the grid on the log dump with the depositional areas being shaded. Both the slope profile and grid show alternating zones of erosion and deposition.

DISCUSSION

The ^{137}Cs results at both Monkerai and Bothwell indicate that the slope profiles exhibit alternating zones of ^{137}Cs enrichment and depletion (Fig. 3). These zones indicate areas of erosion and deposition, respectively. At Monkerai (Fig. 3), the erosional and depositional zones are often out of phase on adjacent transects. At Bothwell (Fig. 3), there is a perfect phase relationship between these erosional and depositional zones on both transects down to site 6, but below this, they are also out of phase. The erosion pin results for the grid on the log dump (Fig. 2) demonstrate that such out of phase relationships between adjacent transects is not uncommon. Clearly, sediment movement on hillslopes is spatially variable due to localized changes in slope, ground cover, vegetation, microtopography, etc. Litter dams and microterraces (Mitchell & Humphreys, 1987) are examples of small scale depositional environments and rills are examples of small scale erosional environments. Such features have a restricted spatial distribution and the resultant pattern of erosion and deposition should be very localized. Therefore, adjacent slope transects should not be expected to necessarily exhibit similar patterns of erosion and deposition.

The erosion pins on the hillslope at Grafton (Fig. 1(c)) were spaced much closer together than the ^{137}Cs sample sites and span a much shorter time period. With this greater spatial and temporal resolution, alternating zones of erosion and deposition were again detected. This indicates that, following disturbance, only one or two runoff-producing events are needed to segregate slopes into discrete erosional and depositional zones.

While the differences in ^{137}Cs values between transects may be caused by localized variations in atmospheric fallout, such pronounced small scale differences have not been previously reported. Therefore, it is proposed that these alternating zones of ^{137}Cs enrichment and depletion are identical to the erosional and depositional pulses on the Grafton hillslope and represent sediment slugs. Sediment moves down these grazed and logged hillslopes as discrete bodies over both short (i.e. individual events) and medium time scales (i.e. 40 years). These depositional bodies are called sediment slugs after the sand slugs documented in rivers by Erskine (1993, 1994).

Pickup (1988) found that sediment moves as a series of scour-transport-fill sequences in the arid zone. These sequences were described on a regional level and extended up to several kilometres in length. Clearly they also exist on a much smaller scale on hillslopes.

The erosion pin results at Grafton should not be interpreted as indicating that deposition dominates on the whole slope. Field observations indicate that in situ soil is more compacted and consequently has a greater bulk density than loose sand deposits. However, when erosion pin results are averaged for a complete slope profile from drainage divide to river channel, erosion always dominates. It is only when grids or part profile results are cited (as in the present case) that deposition dominates.

Although not reported here, the authors also have three years of erosion pin results for three slope profiles at Grafton under native forest. Logging and wildfire have increased soil erosion rates by at least a factor of two and up to a factor of 10 over those for native forest. However, the erosion pin results for native forest still exhibit alter-nating zones of erosion and deposition. Furthermore, the erosion pin results for complete slope profiles show that erosion dominates on profile convexities while deposition dominates on profile concavities. Therefore, systematic differences in erosion and deposition are to be expected, depending on the location of the erosion pins on the profile.

CONCLUSIONS

A combination of ^{137}Cs and erosion pin results for three hillslopes in southeastern Australia showed that sediment may move downslope in a series of slugs or pulses. Local source or erosional zones supply sediment to depositional zones immediately downslope. These alternating erosional and depositional zones can occur during individual events as well as over 40 year time periods, and appear to be detectable over distances of metres to kilometres.

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