Using ^{137}Cs and ^{210}Pb$_{ex}$ measurements to document erosion rates for different time windows in a small catchment in southern Italy

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Abstract In the last decades, climate change has begun to play a significant role in modifying the sediment dynamics of catchments and river basins in many areas of the world. These changes affect both the rates of soil redistribution within catchments and the magnitude of the downstream sediment load. Quantifying erosion rates over large areas commonly represents a considerable challenge as it requires long-term monitoring using experimental plots and related expensive field equipment. In recent years, the fallout radionuclides caesium-137 (^{137}Cs) and unsupported lead-210 (^{210}Pb$_{ex}$) have been successfully used to document rates of soil loss by sheet and rill erosion, both as an alternative to conventional measurements and for calibrating physically-based soil erosion models. This paper describes the use of ^{137}Cs and ^{210}Pb$_{ex}$ measurements to assemble information on soil erosion and soil redistribution during recent decades, within a medium-scale (14.8 km^2) catchment located in southern Italy. Data available from sediment monitoring undertaken at the catchment outlet during the period 1961–1979 were used to estimate the longer-term catchment sediment yield. This estimate has been combined with the information provided by the ^{137}Cs and ^{210}Pb$_{ex}$ measurements, to establish sediment budgets for the catchment. The results provided by the ^{210}Pb$_{ex}$ measurements indicate higher erosion rates than those documented using the ^{137}Cs measurements. Because of its short half-life of 22.3 years, the radionuclide ^{210}Pb$_{ex}$ has been shown to be more sensitive to erosion occurring during the past 15–20 years. These findings are consistent with the increased annual erosivity documented in southern Italy during the last 20 years, causing increased erosion rates in recent years.

Key words caesium-137; excess lead-210; erosion rates; sedimentation rates; sediment budget; Italy

INTRODUCTION

In recent years, climate change has attracted increasing attention from the scientific community, because of its important impact on human activities. The changes in precipitation trends observed by hydrologists in several areas of the globe, which indicate a general increase in the intensity, frequency, and/or duration of major storms, have important implications for environmental hazards such as floods, landslides, and land erosion. The latter includes both rates of soil loss and sediment redistribution within catchments and the magnitude of the downstream sediment load. Floods and land erosion problems are also influenced by other factors such as land-cover change, urban expansion, and social factors that make it difficult to assess the precise causes of any apparent change, especially in the absence of field measurements. Documenting changing erosion rates over large areas represents an important requirement for understanding the effects of climate change on the land surface. Experimental plots and related equipment provide one means of obtaining information on erosion rates (Cinnirella *et al.*, 1998), but many problems exist in extrapolating such data to the wider landscape. The search for other methods of documenting rates of soil loss that are more representative of the natural landscape has directed attention to the use of fallout radionuclides. In recent years, the fallout radionuclides caesium-137 (^{137}Cs) and unsupported or excess lead-210 (^{210}Pb$_{ex}$) have been successfully used in many different areas of the world to document rates of soil loss by sheet and rill erosion. The different origins and properties of these two fallout radionuclides also offer the potential to obtain estimates of soil redistribution rates related to different time windows and thus document recent changes. This paper describes the use of ^{137}Cs and ^{210}Pb$_{ex}$ measurements to assemble information on soil erosion and soil redistribution during recent decades, within a medium-scale (14.8 km^2) catchment located in southern Italy. Data available from sediment (turbidity) monitoring undertaken at the catchment outlet during the period 1961–1979 are used to estimate the longer term catchment sediment yield. This estimate is combined with the information provided by the ^{137}Cs and ^{210}Pb$_{ex}$ measurements, to establish sediment budgets for the catchment for different time windows and to investigate possible effects of climate change on the sediment budget.

THE STUDY AREA

The Alaco catchment (Fig. 1), located in Calabria (southern Italy), has a drainage area of 14.8 km^2 and ranges in altitude from 1242 m a.s.l. at the highest point to 924 m a.s.l. at the catchment outlet. Geologically, approx. 90% of the catchment is underlain by granitoids (Polia-Copanello Unit and Stilo Unit) (Calcaterra *et al*., 1996), which produce soils that are typically characterized by a range of textures. Sandy and sandy-silt soils are, however, dominant. The catchment is uncultivated and large areas are covered by pines (*Pinus laricio* P.), beech (*Fagus sylvatica* L.) and oak (*Quercus* spp.). The rainy season extends from October to March and the mean annual rainfall, for the period 1961–1982, measured at Mammone (38°34′54″N, 16°26′39″E), is approx. 1900 mm (SIMI, 1920–2000).

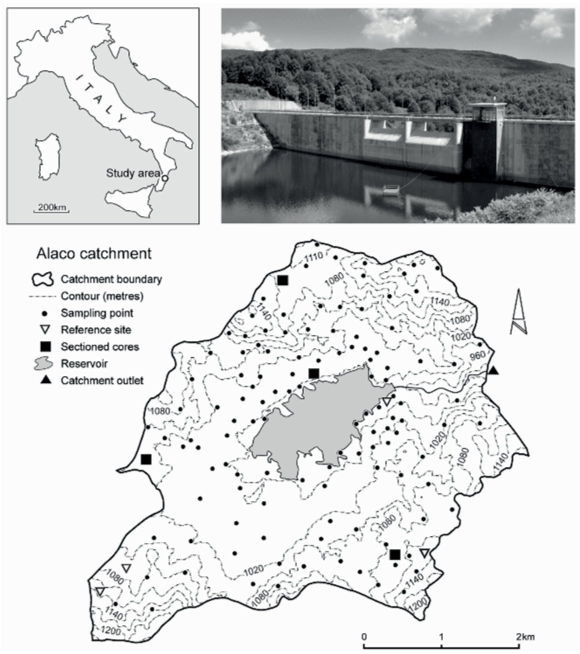

Fig. 1 The study catchment and the soil sampling points.

In 2004 a reservoir that stores approx. 35 million m^3 of water was built in the central part of the catchment, to supply the local population of the towns located downstream. To support the design of this and other dams in the region, the Italian Hydrographic Service (SIMI) undertook measurements of rainfall, runoff and suspended sediment concentration at the catchment outlet during the period 1961–1979. During this monitoring period, the annual specific suspended sediment yield, derived from the sediment concentration measurements, ranged from 8.5 t km^{-2} year^{-1} in 1979 to 358 t km^{-2} year^{-1} in 1973, with a mean annual value of 72 t km^{-2} year^{-1}.

THE SOIL SAMPLING PROGRAMME

Soil sampling for ^{137}Cs and ^{210}Pb$_{ex}$ analysis

Soil sampling for ^{137}Cs and ^{210}Pb$_{ex}$ analysis in the Alaco catchment involved three separate sampling campaigns. The first, undertaken in 2011, focused on establishing the magnitude and spatial distribution of soil redistribution rates within the catchment. During this campaign, replicate bulk soil cores were collected at 120 sites (Fig. 1) using a 11 cm diameter steel core tube inserted to a depth of ≥45 cm using a motorized percussion hammer. The second campaign, undertaken in late 2011, aimed to establish both the magnitude and the depth distribution of the ^{137}Cs and ^{210}Pb$_{ex}$ inventories at four undisturbed reference sites with minimum slope (Fig. 1). For each site, eight separate cores were collected from an area of approx. 25 m^2 using an 11 cm diameter steel core tube inserted to a depth of 60 cm, in order to take account of micro-scale variability in the reference inventory (cf. Owens & Walling, 1996). Each core was sectioned using the same depth increments, which ranged from 1 to 4 cm, and the individual depth increments from the eight cores were bulked. The third sampling campaign, undertaken in 2012, aimed to provide additional information about the depth distribution of ^{137}Cs and $^{210}Pb_{ex}$ in the soils of the catchment. During this campaign, additional depth incremental composite soil samples were obtained from four representative eroding and depositional sites. All bulk core and depth incremental samples collected in the catchment were oven dried at 105°C for 48 h, disaggregated and dry sieved to separate the <2 mm fraction. A representative sub-sample of this fraction (approx. 0.1 kg) was used to determine its ^{137}Cs and $^{210}Pb_{ex}$ activity by gamma spectroscopy in the radiometry laboratory of the Geography Department at the University of Exeter.

RESULTS

^{137}Cs and $^{210}Pb_{ex}$ inventories and depth distributions at the reference site and within the study catchment

The ^{137}Cs and $^{210}Pb_{ex}$ reference inventories for the Alaco catchment based on the composited slices of the cores collected from the four reference sites are listed in Table 1. Considering the various uncertainties involved, a 10% precision error has been attached to these values (Porto *et al.*, 2013).

Table 1 ^{137}Cs and $^{210}Pb_{ex}$ inventories for the Alaco catchment.

	Reference inventory		Inventories within the catchment		
	Mean (Bq m^{-2})	Range (mean ±10% uncertainty) (Bq m^{-2})	Mean (Bq m^{-2})	Range (Bq m^{-2})	Standard deviation (Bq m^{-2})
^{137}Cs	5795	5215–6375	4619	166–18 226	2904
$^{210}Pb_{ex}$	10 787	9708–11 866	7489	52–43 801	6102

Representative ^{137}Cs and $^{210}Pb_{ex}$ depth distributions for the four reference sites are presented in Fig. 2(a) and (b). These are typical of an undisturbed site (Walling & Quine, 1993; Porto *et al.*, 2001, 2003), with approx. 95% of the total inventory existing in the top 10 cm and a sharp exponential decline in activity occurring below this depth (Di Stefano *et al.*, 2000).

The values of ^{137}Cs inventory associated with the 120 sampling points in the study catchment ranged from 166 to 18 226 Bq m^{-2}, with a mean value of 4619 Bq m^{-2} (see Table 1). The equivalent values for $^{210}Pb_{ex}$ ranged from 52 to 43 801 Bq m^{-2}, with a mean value of 6102 Bq m^{-2}. Considering the uncertainty of ±10% at the 95% level of confidence associated with the reference inventories, the measured inventory for an individual sampling point was assumed to be significantly greater or less than the reference inventory only when it falls outside this uncertainty range. The results indicated that 15% of the ^{137}Cs inventory values obtained for the individual sampling points were not significantly different from the reference value, indicating that those sampling points were essentially stable with no significant erosion or deposition occurring. However, 63% of the inventories were significantly lower than the reference value, indicating erosion, and 22% were significantly greater, indicating deposition. That 85% of the sampling points showing evidence of either erosion or

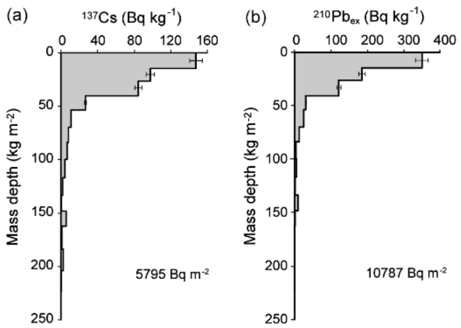

Fig. 2 Representative ^{137}Cs (a) and $^{210}Pb_{ex}$ (b) depth distributions for the reference sites. The error bars depict the 95% confidence limits of the measured radionuclide activities.

deposition confirms that considerable soil redistribution has occurred within the study basin since the commencement of ^{137}Cs fallout in the mid 1950s.

Using the same procedure, the results provided by the $^{210}Pb_{ex}$ measurements indicated that 10% of the sampling points were characterized by inventory values that were not significantly different from the reference inventory and therefore showed no evidence of erosion or deposition. However, 77% of the measured inventories were significantly less than the appropriate reference inventories, providing evidence of erosion, and 13% were significantly greater, providing evidence of deposition. The distribution of sampling points between the stable, eroding and depositional categories is consistent between the two radionuclides, despite their different half-lives and temporal patterns of fallout.

Estimating erosion and deposition rates using the measurements of ^{137}Cs and $^{210}Pb_{ex}$ inventory obtained for the sampling points within the study catchment

Estimation of erosion and deposition rates from ^{137}Cs and $^{210}Pb_{ex}$ measurements is generally based on the degree of reduction or increase of the measured inventory, relative to the local reference inventory. In this study, a conversion model for uncultivated land originally proposed by Walling & He (1999) and refined by Porto *et al*. (2003) was used to convert the magnitude of the reduction or increase in the ^{137}Cs and $^{210}Pb_{ex}$ inventory to an estimate of the rate of soil loss or deposition. Further details of this model can be found in Porto *et al*. (2003, 2006).

The range of the erosion and deposition rates estimated for the individual sampling points within the study catchment, based on the ^{137}Cs and $^{210}Pb_{ex}$ measurements, are presented in Fig. 3(a) and (b). The central class designated stable represents those sampling points where the measured inventories fell within the uncertainty range allocated to the appropriate reference inventory.

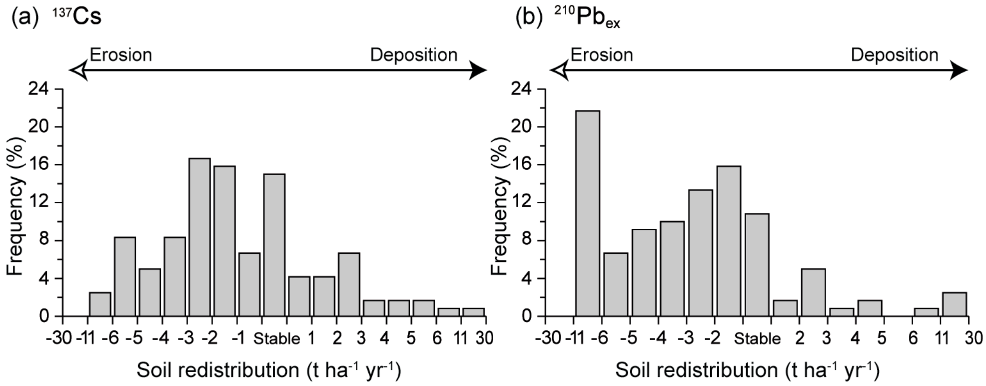

Fig. 3 The range of erosion and deposition rates (t ha^{-1} year^{-1}), estimated using the ^{137}Cs (a) and $^{210}Pb_{ex}$ (b) inventories for the sampling points within the study catchment.

DISCUSSION

The results reported in Table 1 and Fig. 3 indicate that appreciable rates of sediment mobilisation have occurred throughout the catchment during the last decades. Erosion is dominant, but the presence of points documenting deposition emphasises that a proportion of the sediment mobilised within the catchment by erosion is deposited elsewhere within the catchment. The data provided in Fig. 3 (a) and (b) have been combined with the estimate of the mean annual sediment yield derived from the SIMI measurement programme at the catchment outlet to construct the catchment sediment budgets presented in Fig. 4 (a) and (b), which are based on the ^{137}Cs and $^{210}Pb_{ex}$ measurements, respectively. The product of the mean erosion rate for the sampling points characterized by erosion and the area of the catchment subject to erosion, as indicated by the proportion of the sampling points evidencing erosion, has been used to calculate the gross erosion from the catchment slopes. The same approach was applied to deposition within the catchment, to derive an estimate of the total deposition on the catchment slopes. Subtraction of the total deposition within the catchment from the gross erosion provides an estimate of the net erosion, which is here interpreted to represent the sediment delivered to the channel system. Sediment deposition and storage within the main channel system and on the small flood plains bordering the channel have been estimated as the difference between the net erosion and the measured mean annual sediment output from the catchment, and this is seen to represent the conveyance loss within the channel system.

Considering the rate of gross erosion in the catchment, and the proportion of sediment entering storage both on the slopes of the catchment and in the channel system, sediment delivery ratios of 38% and 19% have been obtained based on the ^{137}Cs and $^{210}Pb_{ex}$ measurements, respectively.

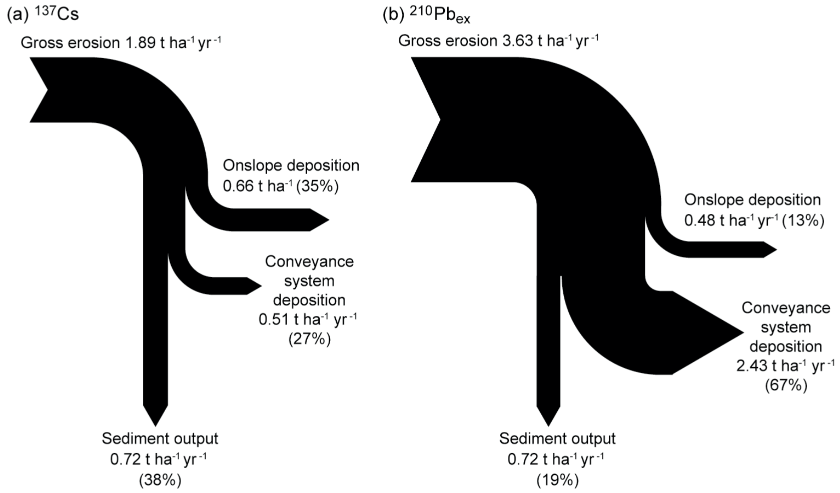

Fig. 4 Schematic sediment budgets for the Alaco catchment derived from the ^{137}Cs (a) and $^{210}Pb_{ex}$ (b) measurements.

It is important to recognise that the estimate of channel system deposition or conveyance loss presented in Fig. 4 has been derived by subtracting the measured sediment output from the catchment from the net soil loss from the catchment slopes. The estimates of the long-term mean gross and net erosion rates derived from the ^{137}Cs measurements relate to a period of approx. 55 years, extending from the commencement of fallout (1954) to the time of sampling. In contrast, because $^{210}Pb_{ex}$ fallout can be considered to be essentially continuous, the equivalent estimates derived from the $^{210}Pb_{ex}$ measurements will reflect a longer period of up to 100 years. However, because of the relative short half-life of $^{210}Pb_{ex}$ (22.3 years), the final estimates of soil redistribition rates derived using measurements of this radionuclide are likely to be more sensitive to erosion and soil redistribution occurring during the past 10–15 years. The higher soil erosion rates estimated using the $^{210}Pb_{ex}$ measurements are therefore seen as reflecting increased erosional activity in recent years, in response to, for example, changing rainfall patterns, or, alternatively, an increased incidence of high magnitude events (Porto & Walling, 2012). This conclusion is supported by evidence of an increase in rainfall erosivity during the last 10–15 years (see Porto & Walling, 2012).

CONCLUSIONS

This study has demonstrated the potential for combining measurements of ^{137}Cs and $^{210}Pb_{ex}$ to provide a means of documenting recent changes in soil erosion rates as a result of climate change. The ability to use the approach retrospecively is a key advantage of the approach, since in many locations reliable information on soil redistribution rates and their changes through time does not exist.

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