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Using radiotracers ^{137}Cs and ^{210}Pb$_{ex}$ to document climate change in mountain areas through the estimate of soil erosion rates

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Abstract. During the last few decades, a general increase in heavy rainfall events has been documented in many areas of the world. These events have caused changes in soil erosion rates and strongly affected the human activities in mountain areas by reducing the national income obtained from cultivated land. In this context, the use of fallout radiotracers can be an important tool for better understanding the consequences of climate change in these areas and proposing effective countermeasures in order to reduce soil loss. In this contribution, plot experiments carried out in southern Italy that involve the use of ^{137}Cs and ^{210}Pb$_{ex}$ measurements were performed to estimate soil erosion rates during the last few decades. The overall results indicate an increase in soil erosion rates during the last 15–20 years and suggest the use of this technique to detect climate change in mountain areas.

1 Introduction

The global fallout of the artificial radionuclide caesium-137 (^{137}Cs; half-life of ca. 30.2 years), associated with the testing of nuclear weapons performed during the period 1954–1980, has now been successfully used as the basis for estimating soil erosion rates in many areas of the world (IAEA, 2014; Ritchie and Ritchie, 2005). Important advantages of the approach include, firstly, the potential to obtain retrospective information on soil erosion rates on the basis of a single site visit; secondly, the spatially distributed nature of the data generated; and, thirdly, the ability to collect data from the "natural" landscape without the need to establish long-term monitoring using experimental plots or catchments that have been proven to be very expensive and time-consuming. In nearly all situations, the resulting estimates of the soil erosion rate represent values of mean annual erosion for a time window representing the period elapsed between the onset of significant ^{137}Cs fallout in the mid-1950s (or the occurrence of peak ^{137}Cs fallout in the early 1960s) and the time of sample collection.

The similar behaviour of fallout lead-210 (^{210}Pb; half-life ca. 22 years) in soils makes it a potential alternative to ^{137}Cs for soil erosion investigations in areas where ^{137}Cs measurements encounter problems. In fact, thanks to its continuous fallout (depending only on precipitation); its estimates cover a longer period (ca. 110 years = 5 half-lives); and, therefore, its combined use with ^{137}Cs can provide important suggestions in an extended time window. The potential to obtain estimates of soil erosion rates related to different time windows can also be exploited to document possible recent changes in soil loss due to variation in land use and/or due to climate change. In fact, by virtue of its shorter half-life, ^{210}Pb$_{ex}$ results more sensitive to soil erosion rates occurred during the last 15–20 years, and the problem of documenting changing erosion rates over such period can be addressed.

This paper describes this technique based on the use of ^{137}Cs and ^{210}Pb$_{ex}$ measurements collected within some experimental plots located in two mountain areas of southern Italy.

Figure 1. The location of the two study areas in southern Italy.

2 The study areas

The investigation was carried out in two study areas (Mongiana and Ferraina) located across the Calabrian Apennine mountain and both covered by beech (*Fagus sylvatica*) and pine (*Pinus nigra laricio*) forests (Fig. 1). Both areas experience a temperate climate, with mild to warm summers and cool winters.

In the experimental site of Mongiana (range of elevation = 850–1050 m a.s.l.), three areas (3 ha in size) have been identified. In each area, three plots have been established to document soil erosion rates in three sub-areas in response to different silvicultural thinning practised during the last 30 years. The sub-areas consist of an undisturbed zone (control), here selected as a reference site; a zone with a traditional thinning (namely Plot 1), in which a cutting with moderate intensity was operated; and a zone with an innovative treatment (namely Plot 2), in which ca. 27 % of the total biomass was removed.

In the experimental site of Ferraina (range of elevation = 1360–1465 m a.s.l.), four plots, including two stands with Calabrian pine of different canopy covers and two stands with beech (one of which was cut in 2009), have been established. More specifically, the two pine forest stands, namely Plot 1 and Plot 2, are characterized by 50-year pine trees planted in the late 1960s during a massive reafforestation programme (ca. 150 000 ha). The two beech forest stands, namely Plot 3 (beech forest clear-cut) and Plot 4 (beech forest undisturbed) consisted of seminatural high beech forests (ca. 140 years old). Plot 4 was not disturbed by cutting activities, except for a minimum removal of trees in the past few decades; on the contrary, Plot 3 was clear-cut in 2009 and then left to evolve naturally.

3 The sampling and analysis programme for ^{137}Cs measurements

The sampling programme for ^{137}Cs and ^{210}Pb$_{ex}$ measurements comprised several field campaigns aimed at collecting soil samples to characterize an undisturbed location (reference site) and the plots themselves.

The sampling was undertaken in May 2018 in the experimental area of Mongiana and in June 2018 in Ferraina using the sampling strategy illustrated in Fig. 2.

Totally, eight final composite soil cores (six from the plots and two from the reference areas) were taken with a 10 cm diameter steel core tube driven into the soil to a depth of ca. 35 cm. Each composite core taken from the plots consisted of three single-sectioned cores combined layer by layer. Each sectioned core consisted of ca. 15–20 layers of 2 cm each. In the site of Ferraina, six additional composite bulk samples were collected for each plot to account for spatial variability. The composite core collected in the two reference areas consisted of nine single-sectioned cores combined layer by layer.

All samples provided by the sampling campaigns, namely the composite bulk cores and the sectioned cores, as well as the samples collected from the reference site were initially oven-dried at 105 °C, disaggregated, homogenized and passed through a 2 mm sieve. A representative fraction of the <2 mm fraction of each sample was then placed into a 0.5 L Marinelli beaker or, in the case of smaller samples, plastic pots (330 cm^3) for determination of their ^{137}Cs and ^{210}Pb$_{ex}$ activity. Before the analyses, the samples were sealed for 3 weeks based on the standard requirements for ^{210}Pb$_{ex}$ measurements. The samples were analysed at the Department of Agriculture of the Mediterranea University in Reggio Calabria, Italy, using high-resolution high-purity germanium (HPGe) detectors. The total inventory (Bq m^{-2}) of each bulk core (see Table 1) was calculated as the product of the measured ^{137}Cs activity (Bq kg^{-1}) and the dry mass of the <2 mm fraction of the bulk core (kg), divided by the surface area associated with the core (m^2).

4 Results

4.1 ^{137}Cs and ^{210}Pb$_{ex}$ inventories at the reference sites and within the study plots

Information regarding the depth distribution of ^{137}Cs and ^{210}Pb$_{ex}$ at the reference sites is reported in Fig. 3 for both study areas.

The total inventory associated with the ^{137}Cs profiles is estimated to be 5949 Bq m^{-2} for Ferraina and 4697 Bq m^{-2} for Mongiana (see Table 1). For the ^{210}Pb$_{ex}$ profiles, the total inventory is estimated to be 10 168 Bq m^{-2} for Ferraina and 14 400 Bq m^{-2} for Mongiana. Table 1 provides a summary of the mean, the range and the standard deviation of

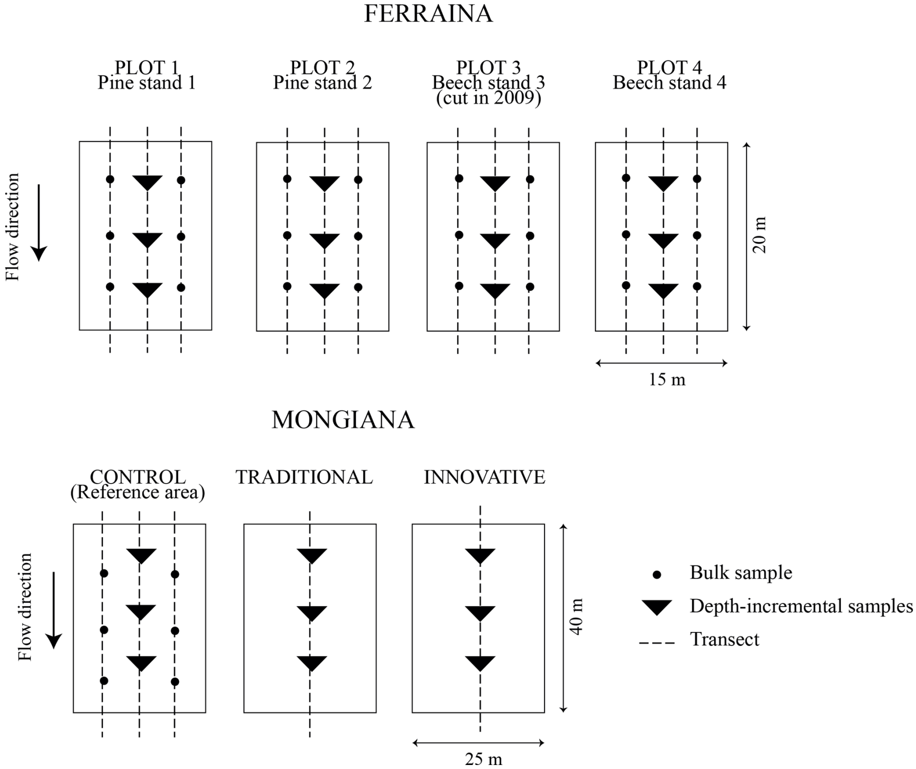

Figure 2. The sampling design within the experimental plots and in the reference areas.

Table 1. ^{137}Cs and $^{210}Pb_{ex}$ inventories for the reference site and for the study plots.

	^{137}Cs				$^{210}Pb_{ex}$			
	Reference inventory	Inventory across the plots			Reference inventory	Inventory across the plots		
		Mean	Range	SD		Mean	Range	SD
Study area	[Bq m^{-2}]	[Bq m^{-2}]	[Bq m^{-2}]	[Bq m^{-2}]	[Bq m^{-2}]	[Bq m^{-2}]	[Bq m^{-2}]	[Bq m^{-2}]
Ferraina	5949	4656	1374–10 943	2053	10 168	7985	902–16 683	4313
Mongiana	4697	3122	1490–4322	1205	14 400	6837	5020–9229	1784

the ^{137}Cs; the $^{210}Pb_{ex}$ inventories obtained within the experimental plots; and the reference sites for the two study areas.

4.2 Estimating erosion rates from the ^{137}Cs and $^{210}Pb_{ex}$ measurements obtained for the sampling points within the study plots

Estimation of erosion rates from ^{137}Cs and $^{210}Pb_{ex}$ measurements is generally based on the degree of reduction in the measured inventory relative to the local reference inventory. In this study, a diffusion and migration model has been used for the purpose of estimating the soil erosion rates indicated by the ^{137}Cs and $^{210}Pb_{ex}$ inventories measured at the sampling sites (see Porto et al., 2003, 2004, 2006, 2018). The model converts the magnitude of the reduction or increase in the radionuclide inventory relative to the reference inventory to an estimate of the rate of soil loss for uncultivated sites. Further details of this model can be found in Porto et al. (2003, 2018).

The range of the erosion rates estimated for the individual sampling points within the study plots based on the ^{137}Cs and $^{210}Pb_{ex}$ measurements are presented in Fig. 4 for each study area. The dashed lines representing the mean value of these estimates are also superimposed in the graphs for further comparison.

5 Discussion

The results reported in Table 1 and Fig. 4 indicate that appreciable rates of soil erosion have occurred throughout the study plots during the time windows explored by the two radiotracers. These rates (see Fig. 4) are higher for the Mongiana site, where the values of soil loss provided by ^{137}Cs

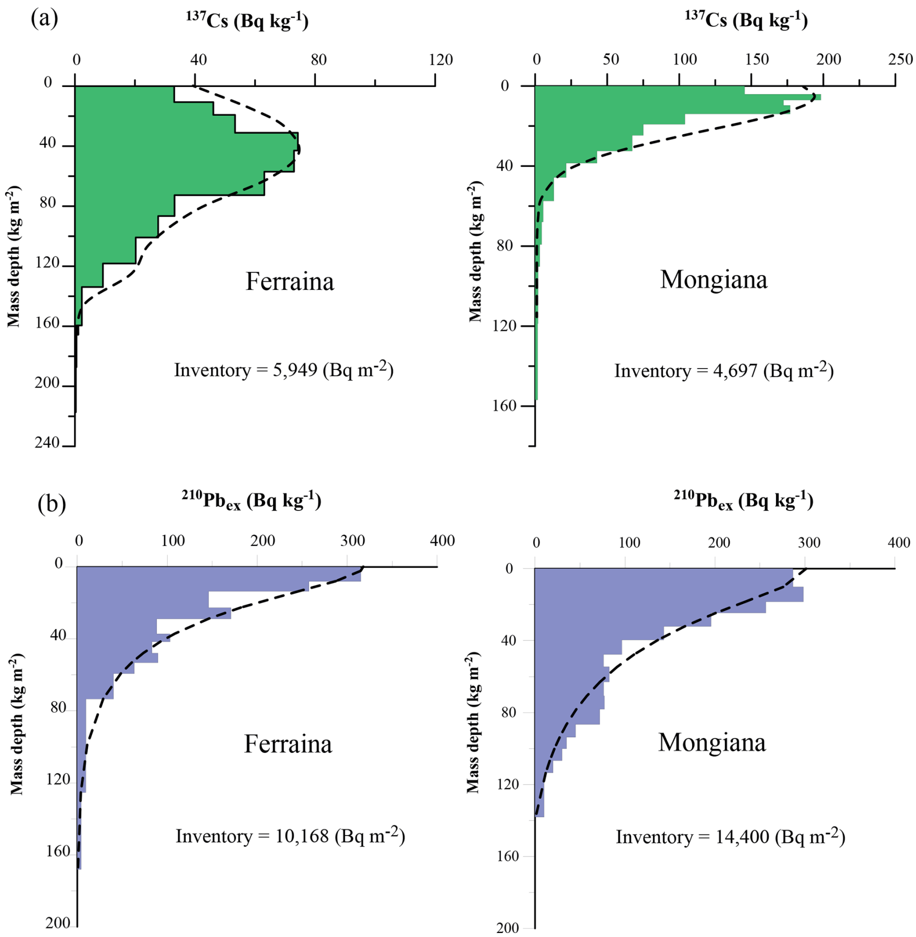

Figure 3. The ^{137}Cs (**a**) and the ^{210}Pb$_{ex}$ (**b**) depth distributions at the reference sites.

range from 2.55 to 9.85 t ha^{-1} yr^{-1}, and those obtained from ^{210}Pb$_{ex}$ measurements range from 6.45 to 10.75 t ha^{-1} yr^{-1}. Equivalent estimates at the Ferraina site provided lower values, ranging from 0.25 to 1.33 t ha^{-1} yr^{-1} for ^{137}Cs and from 0.77 to 3.50 t ha^{-1} yr^{-1} for ^{210}Pb$_{ex}$ measurements. This difference in magnitude between the two sites is related to a number of factors that include difference in rainfall erosivity, change in land use and silviculture treatments, as it was emphasized by Altieri et al. (2018) and Romeo et al. (2021). However, when the comparison is related to the two sets of estimates provided by ^{137}Cs and ^{210}Pb$_{ex}$ measurements within the same study area, it can be seen that overall values of erosion rates obtained with ^{210}Pb$_{ex}$ are higher than those provided by ^{137}Cs. These estimates of mean annual soil loss produced for the two study areas are also outlined in Fig. 4 (see dashed lines). The estimates of the long-term mean erosion rates derived from the ^{137}Cs measurements relate to a period of about 65 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 110 years (ca. 5 half-lives). However, because of the relatively short half-life of ^{210}Pb$_{ex}$ (22.3 years), the final estimates of erosion rates obtained using this radiotracer are likely to be more sensitive to erosion occurring during the past 15–20 years. The higher soil erosion rates estimated using the ^{210}Pb$_{ex}$ measurements are therefore seen as a reflection of increased erosional activity in recent years in response to, for example, changes in rainfall patterns or, alternatively, changes in land use and/or silvicultural treatment (Porto and Walling, 2012; Porto et al., 2009). The increased soil loss evidenced by the experimental plots is consistent with the results of recent studies undertaken in southern Italy, where a trend of increasing rainfall erosivity during the last 15–20 years has been documented (Porto and Walling, 2012; Porto et al., 2013; Capra et al., 2017). In Fig. 5, the annual values of the rainfall erosivity factor (R factor) (Wischmeier and Smith, 1978) for the two stations of Serra San Bruno, located in the Mongiana study area, and of Gambarie d'Aspromonte, located in the vicinity of the Ferraina site, are reported. The calculations of the R factor were made using rainfall datasets related to a duration of 30 min (see Porto, 2016). The histograms presented in Fig. 5 confirm the increasing trend of the annual values of

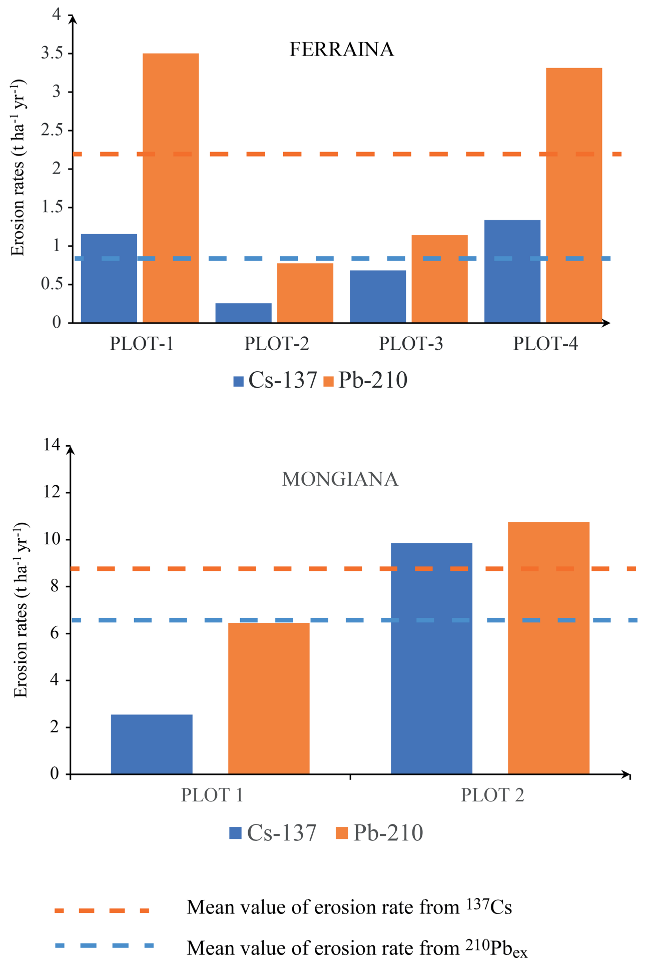

Figure 4. Comparison between the ranges covered by the estimates of mean annual soil loss provided by ^{137}Cs and ^{210}Pb$_{ex}$ for each study area.

the rainfall erosivity factor during the last 30 years for both study areas.

A comparison between the two sets of data also reveals a higher magnitude of rainfall erosivity for the Mongiana site than for Ferraina, where the values of the R factor are ca. 1 : 5 of those of the former. This difference also confirms the higher absolute estimates of soil erosion rates provided by the two radiotracers for the two study areas.

6 Conclusions

The results presented above are seen as a confirmation of the potential for combining ^{137}Cs and ^{210}Pb$_{ex}$ measurements to document recent changes in soil erosion in mountain areas. The results obtained from the ^{210}Pb$_{ex}$ measurements point to higher values of soil loss if compared to equivalent estimates provided by ^{137}Cs. This is consistent with the trend demonstrated by independent information on changes in annual rainfall erosivity in these areas during the last 15–20 years.

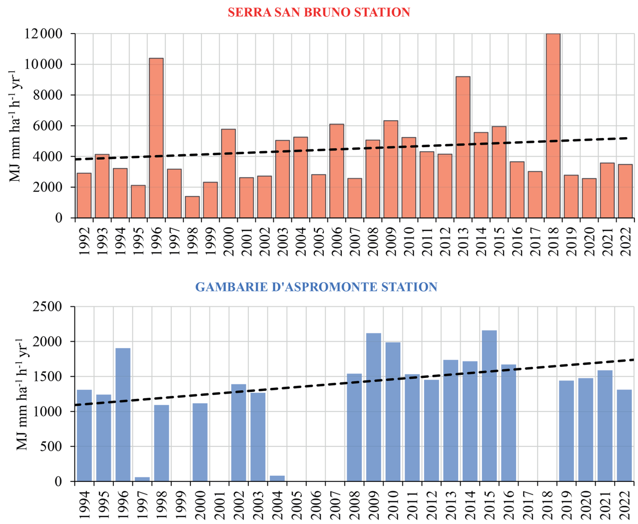

Figure 5. Annual values and trends of the rainfall erosivity factor calculated for the Serra San Bruno station, located in the Mongiana study area, and for the Gambarie d'Aspromonte station, located in the vicinity of the Ferraina site.

Further validation of this approach, particularly in different environments and in areas where soil erosion rates might be expected to be declining, could usefully be undertaken.

Data availability. Data are available upon request from the author.

Competing interests. The author has declared that there are no competing interests.

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