The role of silvicultural systems and forest types in preventing soil erosion processes in mountain forests. A methodological approach using Caesium-137 measurements

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Abstract

Purpose - Forests play a key role in providing protection against soil erosion. Particularly, the role of vertical forest structure in increasing rainfall interception capacity is crucial for mitigating raindrop impact and reducing splash and rill erosion. For this reason, studies on the relationships between forest structures, past management, and the observed rates of soil loss are needed. In the last decades, importance was given to the use of ^{137}Cs as radioactive tracer to estimate soil erosion rates. The ^{137}Cs technique is linked to the global fallout of bomb-derived radiocaesium which occurred during a period extending from the mid-1950s to the late 1970s.

Materials and methods - ^{137}Cs technique, providing long-term retrospective estimates, could be related to forest treatments applied during the last decades in different sites, also considering the tree species composition. This approach could be useful to compare the effect of different canopy cover and biomass on soil erosion rates related to different tree species. In the work proposed here, a study area dominated by pine and beech high forests located in the Aspromonte mountain (Calabria, Italy) was selected. The measurements, related to forest structural traits, focusing on canopy cover and biomass, and also on management approaches and forest types, are compared with rates of soil erosion provided by ^{137}Cs.

Results and discussion - The overall results suggest that minimum values of soil loss are documented in areas with higher canopy cover and biomass evidencing the protective effect provided by forests against soil erosion. Also, techniques based on the use of tracers like ^{137}Cs proved to be helpful to select the best forest management options useful to optimize the protective role of forests, with the aim to reduce erosion processes in a long-term perspective.

Conclusions – However, the experiment indicates that care must be taken when new silviculture treatments are planned. These findings are in agreement with what documented by other authors in similar environments but need further studies to confirm the effectiveness of using ^{137}Cs in different forest ecosystems.

Keywords Apennine forests • Beech forests • Caesium-137• Calabrian pine forests • Silviculture applied • Soil erosion rates

1 Introduction

Forests play a key role in providing protection against runoff and soil erosion (Miura et al. 2003). Soil erosion is a relevant phenomenon in pedogenesis process and affects the evolution of natural ecosystems. Ecological factors like canopy cover, tree species, forest vertical stratification, but also different types of forest management are crucial in increasing rainfall interception and reducing the magnitude of soil loss (Elliot et al. 1999; Hartanto et al. 2003). In the last decades, several studies carried out in forest environments stressed the importance of hydrological functions (Bosch and Hewlett 1982; Moore and Wondzell 2005) and their relationships with soil degradation (Pennock and Van Kessel 1997). The most serious risk, however, is related to soil erosion by water, which is one of the most pressing environmental threats worldwide (Reich et al. 2000). Examples in Mediterranean areas are reported, among the others, by Conacher and Sala (1998) and Montanarella (2007).

The effort to mitigate soil erosion is a prerequisite to provide the self-preservation of forest areas, in order to perform a sustainable forest management. This topic was widely studied in Italy by several researchers (Zanchi 1988; Ollesch and Vacca 2002; Bagarello et al. 2010) and experiments dealing with soil erosion measurements are also available (Alcamo et al. 2007; Sanchis et al. 2008). However, despite the utility of studies carried out in experimental plots and catchments to quantify runoff and soil loss, some difficulties to extrapolate the results in larger areas where no direct measurements are available have emerged. These difficulties are mainly related to the scale effect in the attempts to extrapolate across the landscape modelled rates of water erosion based on plots (see Evans and Boardman 2016; Evans et al., 2016).

The need to test alternative approaches to collect more information on larger areas suggested the use of Caesium-137 (^{137}Cs) to provide reliable estimates of soil erosion both at plot (Porto and Walling 2012a,b) and at catchment scale (Porto et al. 2001; 2009). ^{137}Cs is a manmade radionuclide used for soil erosion assessments in many areas of the world (Zapata et al. 2002; Mabit et al. 2008; Golosov et al. 2013; Alewell et al. 2014) and its feasibility for forest areas has been revealed (Garcia-Oliva et al. 1995; Porto et al. 2001; 2009; Estrany et al. 2016). The use of ^{137}Cs offers a great potential to provide retrospective information on medium-term average of soil loss on the basis of a single sampling without the need to disturb the system by installing measuring equipment. The ^{137}Cs technique makes use of the global fallout of bomb-derived radiocaesium which occurred during a period extending from the mid 1950s to the late 1970s. In most environments, the ^{137}Cs fallout reaching the land surface was rapidly adsorbed by the surface soil and its subsequent redistribution within the landscape will have occurred in association with the erosion, transport and deposition of soil and sediment particles. For forest environments, Porto et al. (2001;

2014) demonstrated the feasibility of the ^{137}Cs approach by comparing estimates of soil erosion provided by the latter with long-term measurements of sediment yield available in small catchments afforested with eucalypt (*Eucalyptus occidentalis* E.). However, to date, no information on the relationships between ^{137}Cs and parameters like canopy cover, tree species, forest vertical stratification and types of forest management are reported.

In this work, a set of four experimental plots in beech and Calabrian pine forest stands was established with the aim to study the relationships between different types of forest management and the observed rates of soil loss using ^{137}Cs.

2 Materials and methods

2.1 Study area

The study area is located in Ferraina, within the Aspromonte National Park, Calabria, Southern Italy (**Fig. 1**). In this site, four rectangular plots (15 m x 20 m), with slope values ranging from 9% to 22%, were established in 2016 (**Fig. 2**). The choice related to the rectangular shape of each plot (with the longer axis parallel to the flow direction) was made with the aim to compare the results of this experiment with those that can be provided by other models like RUSLE (and derived versions) that explore the same range of length and slope.

The forest cover consists of two Calabrian pine (*Pinus nigra laricio* Poir.) stands, with different canopy cover and living biomass amounts, and two beech (*Fagus sylvatica* L.) stands (one of which was cut in 2009). More particularly, the first two plots, namely 'Pine stand 1' and 'Pine stand 2', are covered by Pine forests (ca. 50 years old) planted in the late 1960s during a massive re-afforestation programme (ca. 150,000 ha) carried out in Calabria. The remaining two plots, namely 'Beech stand 3' and 'Beech stand 4', consist of semi-natural high Beech forests (ca. 140 years old) typical of the mountain areas of the Mediterranean basin. Beech stand 4 was substantially undisturbed by cutting activities, with the exception of minimal removal of trees in the past decades; on the contrary, Beech stand 3 was clearcut in 2009 and then left to evolve naturally.

A reference site with no tree coverage was also selected within an undisturbed flat area, located nearby the forested plots, in order to collect information on ^{137}Cs fallout on the overall study area. The elevation of the study area ranges from 1366 to 1465 m a.s.l.. The mean value of annual rainfall, based on the data obtained at Gambarie d'Aspromonte meteorological station (38°07'36''N, 15°57'08''E - 1300 m a.s.l.) and available for the period 1931-

2016, is 1611 mm, with a mean value of annual temperature of 10.6 ˚C. The climate of the area is classified as oceanic temperate. The major soil types are characterised by a silt-loam texture (Soil Survey Staff 1993).

2.2 Soil sample collection for ^{137}Cs analysis

Soil samples were collected in 2016. A detailed sampling programme was established to provide long term data useful to estimate erosion and deposition rates according to the amount of ^{137}Cs in the soil. A total of nine replicate soil cores was collected for each plot, using a 10-cm-diameter steel core tube inserted to a depth of ca. 42 cm. More particularly, three transects aligned with the line of steepest slope were established for each plot. In the central transect, three replicate sectioned cores (each one consisting of 14 x 2 = 28 layers) were collected in order to obtain information on cesium distribution in soil. Six additional replicate bulk cores were also collected from the remaining two transects (see **Fig. 2**).

Even if several studies have emphasized the effect of forest canopy on fallout interception (see among the others Bunzl et al. 1995; Strebl et al. 1999; Takenaka et al. 1998), our samples were collected from small clearings under the trees to reduce this effect. It is worth noticing that the Pine trees on Plot 1 and Plot 2 were planted at the end of '60s when most of ^{137}Cs fallout had already reached the ground. At that time, the ground was similar to that of the undisturbed area selected as reference site. As a result, in these two plots, fallout interception was minimal during the period covered by the trees and the ^{137}Cs inventories are then comparable with those obtained in the reference area (see description below). In Plot 3 and Plot 4, possible fallout interception has occurred due to the longer life of the beech stands (ca. 140 years). However, in Mediterranean areas, most of the rainfall is concentrated in winter time when the deciduous species show no foliage cover. Experimental measurements available for deciduous species (see, for example, Lee 1980; Bruijnzeel and Wiersum 1987) documented values of interception around 10-15% for rainfall higher than 15 mm and for forests with uniform canopy cover. These findings, together with the sampling strategy adopted (consisting of taking samples from small gaps), have probably minimized the effect of fallout interception. However, care was also taken to avoid sampling points close to the tree trunks in order to minimize the effect of stemflow on the final ^{137}Cs inventories.

In order to obtain information on the ^{137}Cs reference value, a detailed soil sampling campaign was also carried out in the reference area located nearby the study plots (elevation = 1400 m a.s.l.). In this case, four separate sectioned cores were collected within a large forest gap, using the same procedure as employed for the sectioned cores

collected in the study plots. This sampling strategy was adopted to account for the micro-scale variability of the atmospheric fallout (see Porto and Walling 2013).

After collection, each core was transported in the laboratory and pre-treated for ^{137}Cs measurements. A total of 384 soil samples (336 from the sectioned cores and 48 bulk cores) were collected for the study plots while 120 samples were obtained for the reference area. All the samples were oven dried at 105 ˚C for 48 h, disaggregated, dry sieved to separate the <2 mm fraction and packed in plastic pots or petri dishes for determination of its ^{137}Cs activity by gamma spectroscopy at the University Mediterranea of Reggio Calabria. The gamma-ray spectrometry equipment used in this study consists of 2 Canberra p-type HPGe detectors, model GX4020. Each detector has 45.6% of relative efficiency with a resolution of 1.1 keV at 122 keV and 2.0 keV at 1.33 MeV and it works coupled to a Desktop Spectrum Analyzer DSA-1000 Canberra multichannel analyzer. The spectral analysis is performed using the Canberra Genie 2000 software package. Each detector has been characterized to permit the efficiency calibration by the Canberra's LabSOCS (Laboratory SOurceless Calibration Software) code that performs mathematical efficiency calibrations of Ge detectors, without any use of radioactive sources by the laboratory user. The energy calibration was obtained using a certified multigamma source with a wide energy range (42.8-1274.5 keV). Also, a further validation phase was performed using the activity concentration for ^{137}Cs of several standard materials of different geometry to cover the specific range of energy of this radionuclide. Count times in the detectors were typically approximately 80000 s and the ^{137}Cs activities were obtained from the counts at 662 keV.

In order to convert ^{137}Cs measurements into soil erosion and deposition estimates, the diffusion and migration model (DMM) originally proposed by Walling and He (1999) and refined by Porto et al. (2003), was used. The DMM simulates the time evolution of ^{137}Cs within a soil profile based on the atmospheric fallout and on its post-depositional redistribution. Porto et al. (2003) reported the following equation to interpret the activity of ^{137}Cs within the soil profile (see also Lindstrom and Boersma 1971; Officer and Lynch 1982; Walling and He 1999):

$$C(x,t,t') = e^{-\lambda(t-t')} \int_0^{\infty} \frac{I(t')}{H} e^{-\frac{y}{H}} \left\{ e^{\frac{V(x-y)}{2D} - \frac{V^2(t-t')}{4D}} \left[e^{-\frac{(x+y)^2}{4D(t-t')}} + e^{-\frac{(x-y)^2}{4D(t-t')}} \right] \times \right.$$
$$\left. \times \frac{1}{\sqrt{4\pi D(t-t')}} - \frac{V}{2D} e^{\frac{Vx}{D}} erfc\left[\frac{x+y+V(t-t')}{\sqrt{4D(t-t')}} \right] \right\} dy \quad (1)$$

where:

C(x,t,t'), expressed in Bq kg^{-1}, is the ^{137}Cs activity related to the mass depth x and time t'.

D ($kg^2\ m^{-4}\ yr^{-1}$) represents the time-averaged estimate of the diffusion coefficient;

V ($kg\ m^{-2}\ yr^{-1}$) is the downward migration rate;

H ($kg\ m^{-2}$) indicates the relaxation mass depth i.e. the ^{137}Cs initial distribution along the soil profile following the atmospheric fallout;

λ (= $0.023\ yr^{-1}$) is the constant of radioactive decay for ^{137}Cs;

x ($kg\ m^{-2}$) is the soil mass depth measured from the soil surface downwards;

t (yr) is the time elapsed since the first fallout;

I(t'), expressed in ($Bq\ m^{-2}\ yr^{-1}$), indicates the ^{137}Cs atmospheric flux at time t'.

erfc(u) is the error-function complement defined as (Crank 1975):

$$erfc(u) = \frac{2}{\sqrt{\pi}} \int_u^{\infty} e^{-y^2} dy \qquad (2)$$

Taking account of a continuous input I(t'), the ^{137}Cs concentration distribution C(x,t) ($Bq\ kg^{-1}$) in the soil profile at time t can be obtained by integrating C(x,t,t') over time t' (Walling and He 1993):

$$C(x,t) = \int_0^t C(x,t,t')dt \qquad (3)$$

The reason of this choice is related to the meaningful results obtained with the use of DMM in southern Italy (see Porto et al. 2003; 2014) and to the visual inspection of the profiles reported in **Fig. 3** and **Fig. 4** that show a peak below the soil surface

2.3 Structural analysis of the study plots

To better represent the forest structure in the plots and to correlate soil erosion estimates provided by ^{137}Cs with the type of forest management in the study area, dendrometric measurements were carried out in the same plots with the exception of Beech stand 3 where no trees are available. All the trees in the plots were georeferenced and measurements of height, and diameter have been carried out. Data were then processed to calculate the values of the Basal Area ($m^2\ ha^{-1}$), Volume ($m^3\ ha^{-1}$), Number of plants per plot, and Number of plants per hectare. Moreover, in order to represent the vertical and horizontal forest structure within the study plots, measures on tree spatial distribution, canopy insertion height and tree canopy projection on the forest soil were also carried out. Data were

then processed through the Stand Visualization System software (USDA, Forest Service) to show the tree spatial distribution for each plot. In addition, hemispherical photos using a fish eye lens were collected and processed with the GLA (Gap Light Analyzer) software for calculating the canopy cover and the leaf area index (LAI).

3 Results

3.1 ^{137}Cs inventories and depth distributions at the reference site and study plots and soil erosion estimates

The four sectioned cores collected within the reference area produced 120 soil samples (2-cm increment). The matching depth increments were bulked prior to gamma assay, and a representative estimate of the local reference inventory and its depth distribution were obtained. This profile, reported in **Fig. 3** together with the fitting provided by the DMM, is typical of an undisturbed site (see Porto et al. 2003). It shows about 90% of the total inventory occurring in the top 15 cm, a peak in activity ca. 6 cm below the soil surface, and a sharp exponential decline in activity below this depth. This profile shows a reference inventory of 5949 Bq m^{-2}, in agreement with what found in other areas of South Italy with similar annual rainfall (see Porto and Walling 2012). As mentioned above, the profile was built on the matching depth increments in order to cover the spatial variability of the atmospheric fallout. However, we considered a 10% uncertainty around this value (see Table 1) to account for the measurements error due to the equipment. The values of ^{137}Cs inventory associated with the samples collected from the plots are reported in **Table 1** while the ^{137}Cs depth distributions associated with each plot are illustrated in **Fig. 4**. The four ^{137}Cs depth distributions in **Fig. 4**, one for each plot, indicate different inventory values but they show a similar shape that conforms to that expected for uncultivated soils.

Information on the ^{137}Cs inventory values for the study plots, provided in **Table 1**, indicates that 29 out of 36 sampling sites (including the profiles in **Fig. 4**) show inventory values lower than the reference value pointing out evidence of soil erosion within the plots. Only 7 points documented evidence of deposition with ^{137}Cs inventories higher than the reference value. A mean value of 4689 Bq m^{-2} (lower than the reference inventory), obtained from the 36 single points, showed that erosion was the dominant process during the time span (ca. 60 years) covered by the ^{137}Cs measurements.

Information on the corresponding estimates of soil loss provided by the DMM is also reported in **Table 1** for each plot.

223 3.2 Structural data of the study plots

224 Data obtained from the structural surveys are listed in **Table 2**. Pine stand 1, Pine stand 2, and Beech stand 4
225 showed respectively a mean diameter of 32.31 cm, 33.27 cm and 36 cm. The same stands showed volume values
226 of 699 m^3 ha^{-1}, 1589 m^3 ha^{-1} and 1080 m^3 ha^{-1} while the number of trees per hectare was 866, 1500 and 933,
227 respectively. The tree canopy cover determined with the use of hemispherical photos and the GLA software was
228 52% for Pine stand 1, 63% for Pine stand 2 and 51% for Beech stand 4. The corresponding values of the leaf area
229 index (LAI) were 0.79 (m^2 m^{-2}), 1.13 (m^2 m^{-2}) and 0.80 (m^2 m^{-2}), respectively.

230

231 **4 Discussion**

232 The results reported in **Table 1** show different values of ^{137}Cs inventories. The significance of these differences
233 was checked, preliminarly, using the Friedman test (see Kanji 1993). The resulting statistics were always higher
234 than the critical value at the 0.05 level of significance, indicating that there were significant difference between
235 the 4 empirical distributions of ^{137}Cs values associated with the plots.

236 The ^{137}Cs measurements carried out in the 9 sampling points selected in each plot provided an estimate of the
237 average soil redistribution rates for the period extending from the commencement of ^{137}Cs fallout in the mid-1950s
238 to the present. As explained above, the use of these measurements was based on the comparison between the
239 radionuclide reference value obtained in the reference area and the ^{137}Cs inventories measured in the 9 single points
240 for each plot. Most of the latter inventories (29 out of 36) were lower than the reference value, indicating that soil
241 erosion was a dominant process during the last ca. 60 years. The mean value of the erosion rates, reported in **Tab.**
242 **1** for each plot, range from 0.38 t ha^{-1} yr^{-1} to 1.34 t ha^{-1} yr^{-1}. These values are generally lower than the annual mean
243 values considered as 'issue of concern' by the scientific literature. Verheijen et al. (1999), for example, even when
244 dust deposition is included in soil formation rates, reported an upper limit of tolerable soil erosion of ca. 1.4 t ha^{-1}
245 yr^{-1}. These findings support strongly the hypothesis that forests play a key role in regulating the runoff and soil
246 erosion, due to the protection offered by the canopy cover and to their capability of improving the absorption
247 capacity of soils. In fact, both these functions are useful to reduce the overland flow and the water erosion risks
248 related. However, some differences between the four forest types selected in this study must be recognised. In
249 order to facilitate the comparison between the four treatments, a spatial visualization of the trees, obtained with
250 the SVS software, is provided in **Fig. 5A-D**. The corresponding spatial distribution of soil erosion rates was also
251 created, using a kriging interpolation procedure, and is depicted in **Fig. 5E-H**.

A first comparison can be made between Plot 1 and Plot 2, having the same forest type (Pine stand) but with different forest cover and biomass. Pine stand 1, characterised by a canopy cover of 52%, shows a mean value of soil erosion equal to 1.16 t ha^{-1} yr^{-1} that is higher than that documented by Pine stand 2 (only 0.26 t ha^{-1} yr^{-1}) where the canopy cover is 63%. The higher value of soil erosion in Pine stand 1 could also be due to a minor tree density (866 trees ha^{-1}) compared to that (1500 trees ha^{-1}) measured in Pine stand 2 (see also Fig. $5_{A,B}$). A higher tree density in fact, enhances the soil protection due, for example, to a stronger root system and a larger surface taken up by the tree canopy that intercepts a higher amount of rainfall and limits the raindrop impact on the ground (see Chapman 1948). The different forest covers and tree density currently found in both pine stands are part of the same type of silvicultural treatment. These differences are probably due to micro-variabilty (e.g. small disturbances and stand dynamic evolution) in that area (Gray and Spies 1996). Anyway, the management of the stand in the past years preserved the protective role of the trees against soil erosion processes. These findings emphasise the conclusion that an increase in forest cover and biomass improves soil protection. The pattern of soil erosion rates depicted in **Fig. $5_{E,F}$** clearly delineates the areas with the highest rates of soil loss within the plots. A close correspondence with the lower values of canopy cover can be observed (see **Fig. $5_{A,B}$**) and this supports the above conclusion.

A second important comparison can be observed between Plot 1 and Plot 4 having similar canopy cover (52% and 51%) but characterised by two different forest species (Pine and Beech, respectively). The mean value of soil erosion in Beech stand 4 (0.68 t ha^{-1} yr^{-1}) is lower than that documented in Pine stand 1 and seems to suggest a better protection against soil erosion offered by the former. A possible explanation of this result can be related to the greater canopy cover capacity expected for deciduous species than for conifers, as documented by other authors (see among the others, Helvey and Patric 1965; Zinke 1967). Another possible reason for these lower values of soil erosion rates can be ascribed to the Beech root system that is generally shallow and superficial, with large roots spreading out in all directions. Conversely, the Pine root system is relatively deeper and does not offer the same protection against erosion of the first soil layers. However, the role of the canopy cover in protecting the soil from erosion is confirmed by the spatial pattern of soil erosion rates depicted in **Fig. 5_{H}** In fact, a comparison with the spatial visualization of the trees in **Fig. 5_{D}** shows, again, a close correspondence of the areas with higher erosion rate with the lower values of canopy cover.

A last important comparison can be made between the Beech stand in Plot 4 and the forest system in Plot 3, originally covered by a Beech stand that was clearcut in 2009. In this case, it was possible to explore the effect reflected by the clearcutting in terms of soil loss from this area. The mean value of soil erosion rate for the Beech

stand 3 is 1.34 t ha^{-1} yr^{-1}, almost double that from Beech stand 4. This result is clearly not unexpected because the temporary lack of canopy cover occurred during the last 7 years may have affected soil properties and this resulted in significant increase of soil loss in recent periods. However, it must be recognised that the last 6-7 years following the clearcutting are characterised by the occurrence of very severe rainfall events that coincided with the absence of vegetation in this area and may have affected strongly the rate of soil loss in the same period. Although no direct measurements of soil erosion are available for the recent years, an attempt to reconstruct the trend of soil loss using the rainfall erosivity factor (Wischmeier and Smith 1978) can be made. This trend is depicted in **Fig. 6** for Gambarie meteo station located in the vicinity of the study site. The dataset of the 30-min rainfall is available from 1991 to date. The clearcutting occurred in October 2009 and **Fig. 6** indicate that for the set of storm events occurred from that period to the sampling date, the mean value of the R-factor (R_m = 4473 MJ ha^{-1} mm^{-1} h^{-1}) was significantly greater than that related to the period 1991-2008 (R_m = 2635 MJ ha^{-1} mm^{-1} h^{-1}). The increase is particularly marked for the events that occurred in 2015, prior to the sampling campaign. Similar trends of the R-factor, whith a general increase during the last decade, have been also documented by Capra et al. (2017) for other stations located in the same region. The higher values of the R-factor, combined with the tree cutting showed a general increase of soil erosion even in other areas, emphasizing the importance of vegetation in protecting the soil (see Porto et al. 2009).

However, further measurements are needed during the next years to establish if the effect of the clearcutting might be mitigated while the new vegetation will take place.

5 Conclusions

The overall results obtained in this experiment demonstrated, first of all, the ability of ^{137}Cs as a tracer technique to predict soil erosion rates. Based on the ^{137}Cs measurements, minimum values of soil loss (0.26 t ha yr^{-1}) are documented in areas covered by Pine stand with higher canopy cover and biomass (Plot 2), evidencing the protective effect provided by forests against soil erosion. The experiment demonstrated that when canopy cover is lower and discontinuous, as in the two cases described in Plot 1 and Plot 4, the ^{137}Cs measurements documented higher values of soil loss, equal to 1.16 t ha^{-1} yr^{-1}, and 0.68 t ha^{-1} yr^{-1}, respectively. These findings indicate that when afforestation programmes or new plantations activities are planned, but also during the silvicultural treatments, it is necessary to reduce the occurrence of large gaps among the forest cover in order to reduce soil erosion. The effectiveness of canopy is also evident in the uncovered area (Plot 3) where the original Beech stand was clearcut in 2009. In this case, the mean rate of soil loss provided by the ^{137}Cs measurements was 1.34 t ha^{-1}

311 yr^{-1}, almost double that in the area (Plot 4) where the same forest type was maintained undisturbed. Although the
312 clearcutting operations occurred in a period during which the rainfall erosivity was the highest in the last 25 years,
313 the experiment indicates that care must be taken when new silviculture treatments are planned. These findings are
314 in agreement with what documented by other authors in similar environments but further work is necessary to
315 establish the effectiveness of ^{137}Cs measurements in different forest contexts.

316

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438 Table 1. ^{137}Cs inventories for the reference area and the study plots, and calculated values of soil redistribution
439 rates (negative values indicate erosion).

	Reference inventories		Inventories within the plots			Soil redistribution rates	
	Mean (Bq m^{-2})	Range (10% uncertainty) (Bq m^{-2})	Mean (Bq m^{-2})	Range (Bq m^{-2})	St. Dev. (Bq m^{-2})	Mean (t ha^{-1} yr^{-1})	Range (t ha^{-1} yr^{-1})
Pine stand 1	5949	5354-6544	4185	1897-10943	2853	-1.20	-2.6 – 3.16
Pine stand 2			5609	3309-10211	2147	-0.26	-1.7 – 2.68
Beech stand 3			3910	1374-6594	1586	-1.34	-3.0 – 0.41
Beech stand 4			4910	2845-7267	1399	-0.68	-2.0 – 0.84

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443 Table 2. Dendrometric values obtained for each plot

Plot	Mean DBH (cm)	Mean H (m)	Basimetric area (m^2 ha^{-1})	Volume (m^3 ha^{-1})	No. of trees per hectare	Canopy cover (%)	LAI (m^2 m^{-2})
Pine stand 1	32.3	19.9	74.1	698.9	867	52	0.79
Pine stand 2	33.3	24.7	138.9	1589.9	1500	63	1.13
Beech stand 4	36.1	22.8	102.6	1080.4	933	51	0.80

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447 **Figure**

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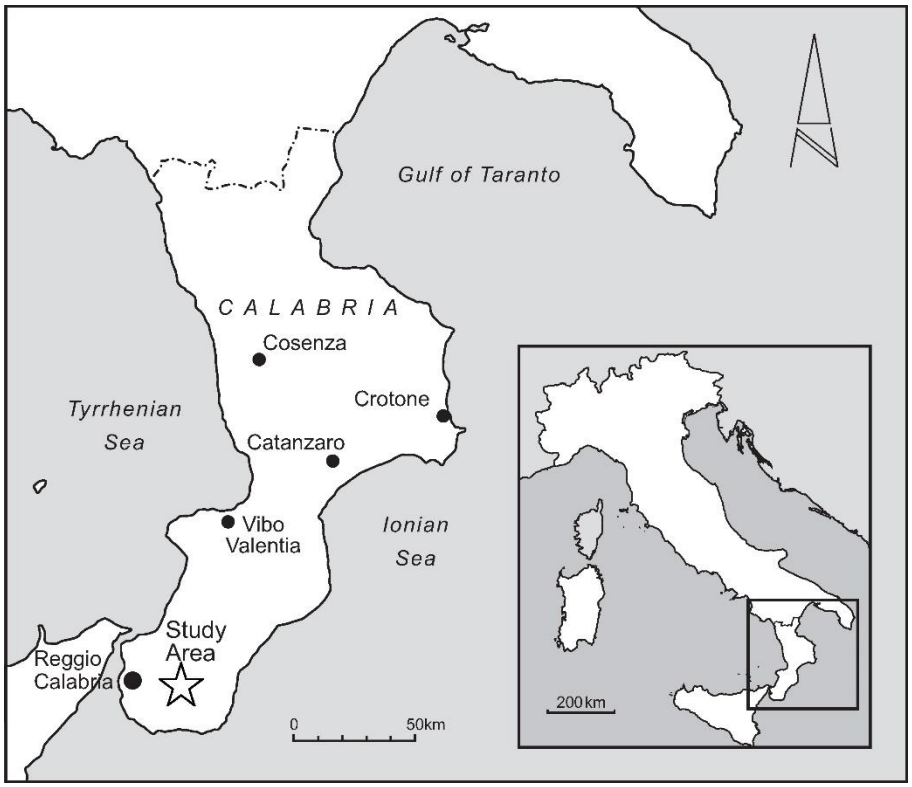

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451 **Fig. 1** The study area

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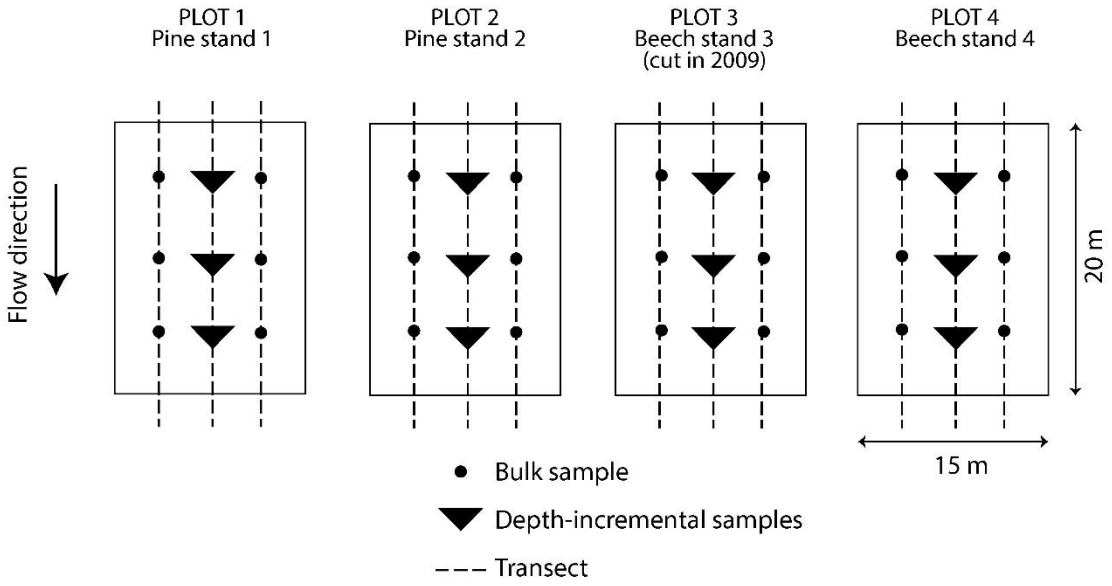

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456 **Fig. 2** The experimental plots and the sampling locations

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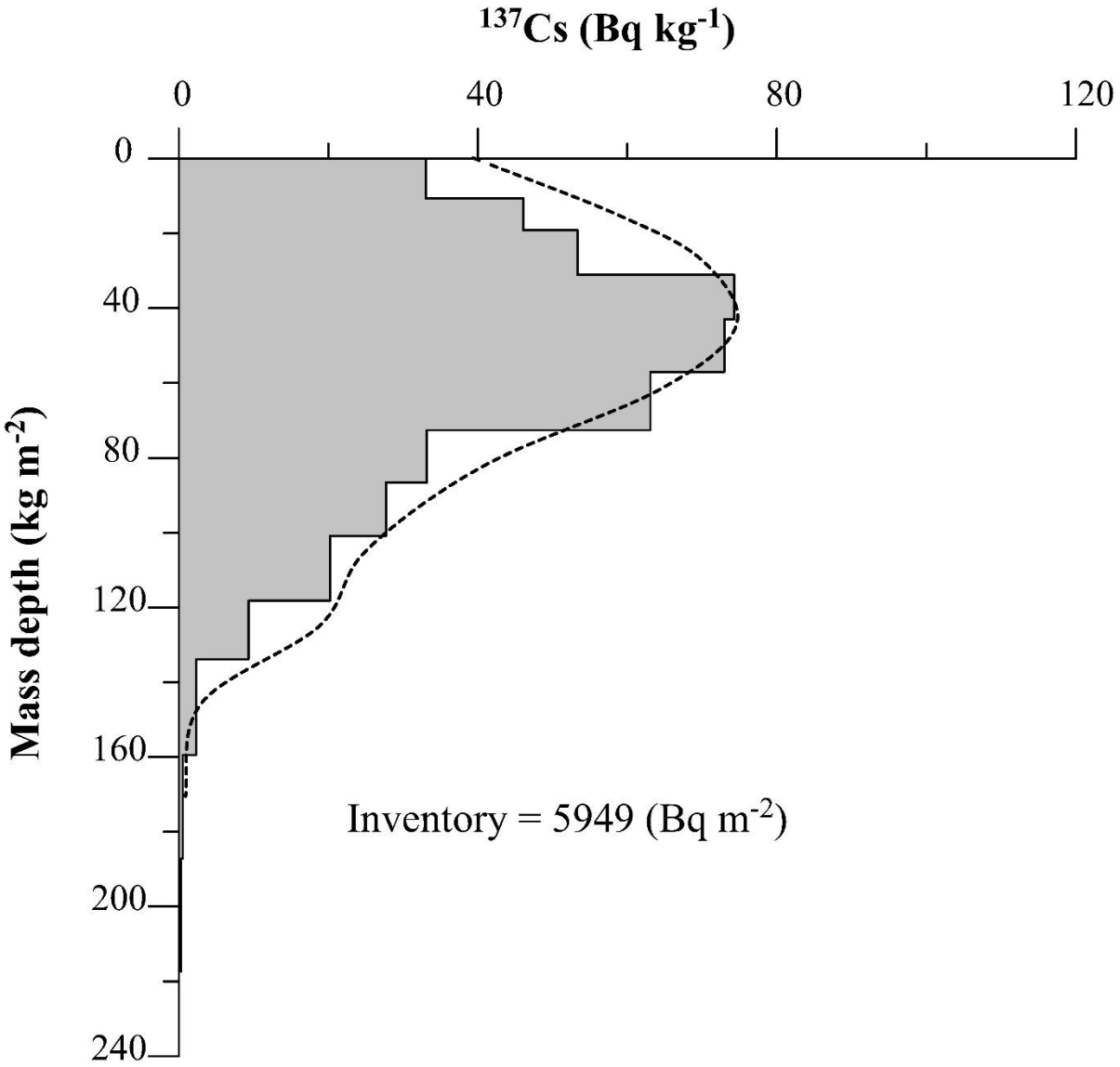
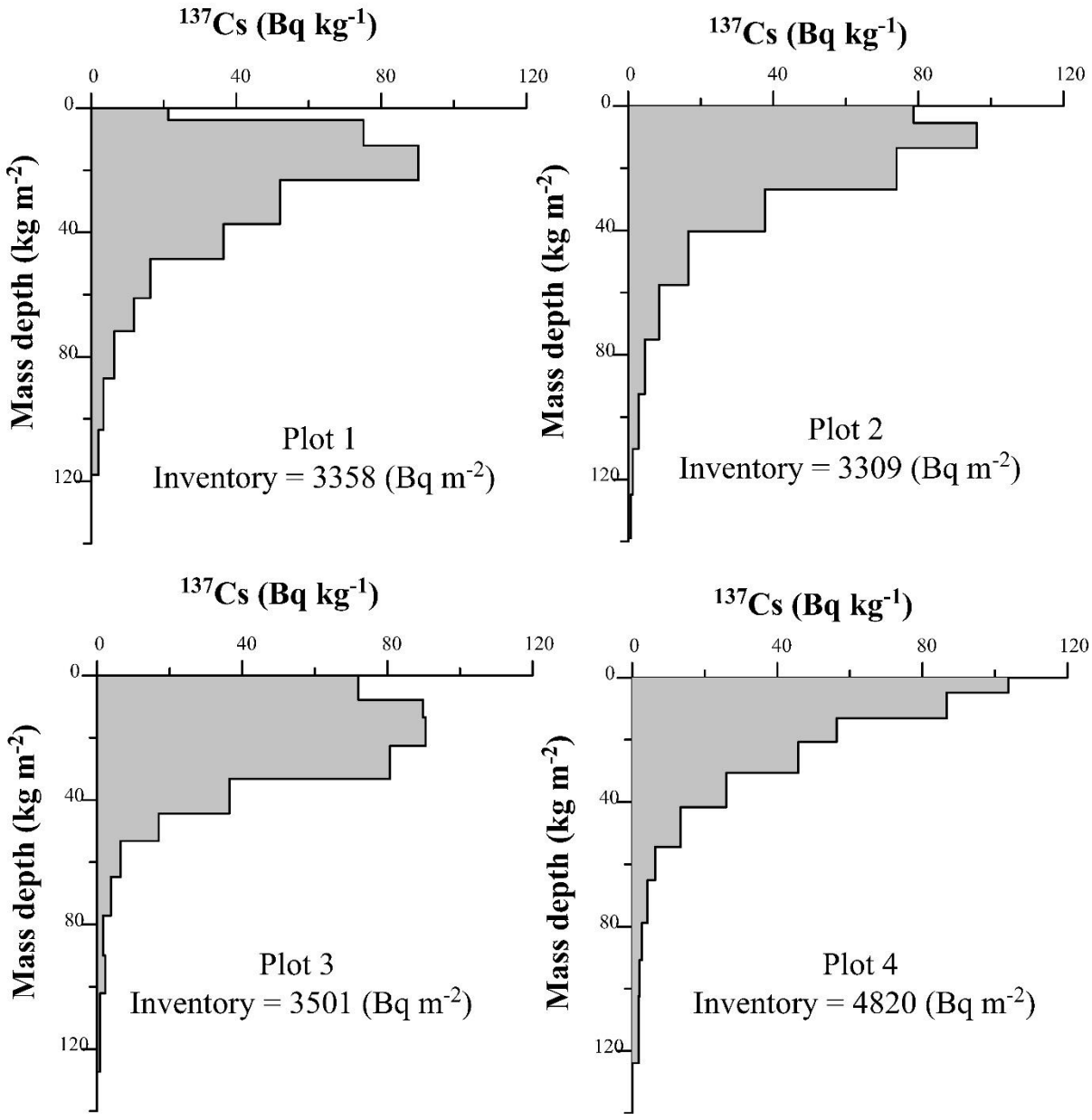


Fig. 3 ^{137}Cs inventory and depth distribution in the reference area



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467 **Fig. 4** ^{137}Cs inventory and depth distribution within the study plots

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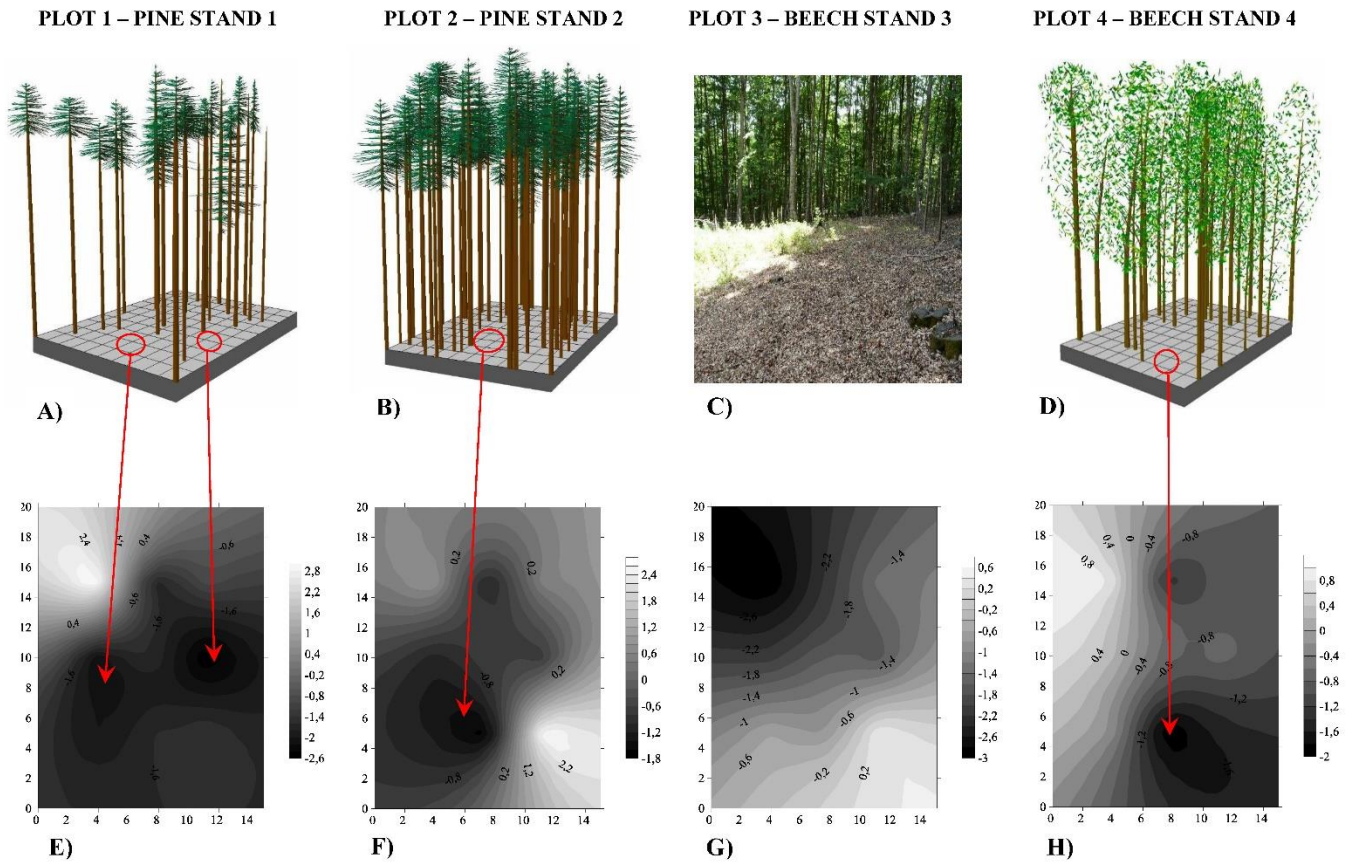

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472 **Fig. 5** Spatial vision of the trees from each plot (A-D) and corresponding spatial distribution of soil erosion (E-H). Figure 5C shows a photo of the Plot 3 where cutting
473 operations were performed in 2009.

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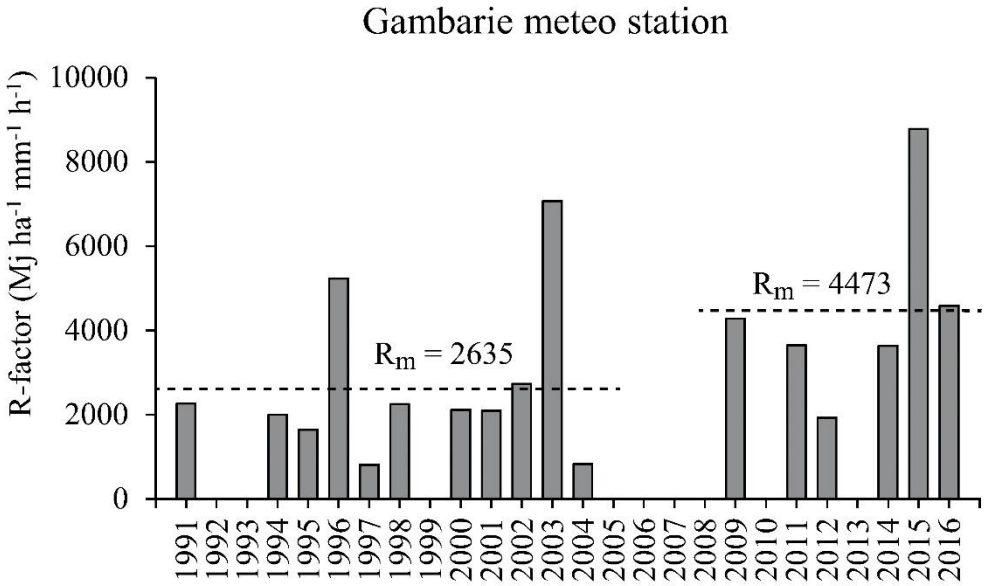

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476 **Fig. 6** Rainfall erosivity factor for Gambarie meteo station

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