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The pattern of soil redistribution along a transect in the central Ebro basin (NE Spain) and its controls

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Abstract The central part of the Ebro basin is threatened by desertification under the scenario of climate change for Mediterranean areas. A survey to examine the pattern of soil erosion and sedimentation was carried out along a climatic and altitudinal transect extending from the centre of the basin to the northern divide in the Pyrenees. Soil redistribution rates were assessed by using fallout ^{137}Cs measurements on representative areas that are presented as case studies. The central steppe is the most severely affected by erosion, as indicated by highly depleted ^{137}Cs levels. In the semiarid area, erosion mainly affects the slopes that are sparsely vegetated and the cultivated valley floors. In the Pyrenees, soils on steep slopes are quite stable under dense shrub or forest cover. On the sparsely vegetated slopes of abandoned fields, erosion is severe, particularly on south facing slopes. These case studies emphasize both the spatial contrasts in soil redistribution rates that can be found in Mediterranean areas and the intense erosion and sedimentation dynamics that can threaten the sustainability of soil and water resources.

Key words caesium-137; Ebro basin; erosion; controlling factors; sedimentation; Mediterranean environments; Spain

INTRODUCTION

Mediterranean countries are the most at risk of the potential environmental changes leading to desertification in Europe. As much as 40% of the territory of Spain is threatened by erosion and among the endangered areas is the central part of the Ebro basin. Some landscapes in this region are highly eroded and the soil here is a non-renewable resource. Soil losses threaten the sustainability of agroecosystems and also give rise to other indirect off-site effects, such as siltation of water bodies, that also have very high economic costs.

According to Nearing *et al.* (2004), global warming is expected to lead to a more vigorous hydrological cycle with more frequent high intensity rainfall events that would increase soil erosion. There is therefore a need to implement soil conservation measures in the context of resource sustainability and this requires information on the extent of soil erosion and redistribution. To address this need, the radiotracing technique has been employed to examine the pattern and extent of erosion and sedimentation in representative environments in the central Ebro basin. The use of ^{137}Cs to trace soil movement has been increasingly and widely applied during the last three decades (e.g. Ritchie *et al*., 1970; Walling & Quine, 1991; Wallbrink, 1997) and its potential for documenting soil redistribution in the Ebro basin has already been demonstrated (Navas & Walling, 1992; Navas *et al*., 1997).

Climate, vegetation cover and land use are key factors in controlling erosion and sediment yields in Mediterranean environments (e.g. Bryan & Campbell, 1986). The central Ebro basin is characterized by a large physiographic diversity, ranging from the arid steppe in the centre of the valley to alpine mountains in the Pyrenees, within a relatively short distance of around 150 km. To conduct this study, three areas characterized by arid, semiarid and temperate conditions along an altitudinal transect have been chosen as representative of this climatic and physiographic diversity. In the areas selected as case studies, fallout ^{137}Cs has been measured in soils with different slope steepness and land use, and with a range of vegetation cover. The soil characteristics and physiographic factors affecting soil redistribution rates have been examined to assess their influence on erosion and sedimentation processes. The aim was to develop a sound scientific basis for promoting conservation measures to preserve both soil and landscape.

THE STUDY AREA

The Tertiary history of the Ebro basin determined the distribution of the parent materials, comprising evaporites (gypsum), carbonates and siliciclastics, from the centre of the basin to its boundary (Fig. 1). The diversity of lithology, climate and topography has given rise to a variety of soil types with different erosive behaviour. In the temperate mountain study area the soils are Kastanozems and Cambisols; in the semiarid study area Regosols and Calcisols predominate; whereas in the arid depressions highly erodible Solonchaks and Gypsisols are found. The landscape also has very distinctive features. The central arid steppe is a vast and almost flat surface with an abundance of endorheic depressions containing saline lakes. The semiarid area is characterized by high Tertiary plateaux connected to the lowlands by gypsiferous hills that are dissected by the Quaternary drainage network. The basin borders coincide with medium height mountains in the Flysch region and alpine mountains in the axial Pyrenees. Table 1 presents some of the main physiographic and terrain characteristics of the study areas. A more detailed description of the soil properties relevant to erosion is provided in Table 2.

In the Ebro basin, the climate varies from the arid regime in the centre of the valley to the temperate continental conditions in the middle mountains (1000 m a.s.l.) with a mean annual precipitation of 1000 mm. In the semiarid areas (480 m a.s.l.), the mean annual rainfall is around 400 mm and in the arid depression at an altitude of 300 m a.s.l., it is less than 250 mm. Reflecting the climate, the slopes of the temperate mountains are covered by dense pine forests, except in the areas of former cultivation that have been abandoned and now support a less dense cover of matorral. In the semiarid area, the slopes are in general sparsely vegetated with shrubs, whereas cereal crops are grown on the valley floors. In the central arid depression, the flat surfaces are extensively cultivated and a few areas around the saline lakes are covered with small saline shrubs.

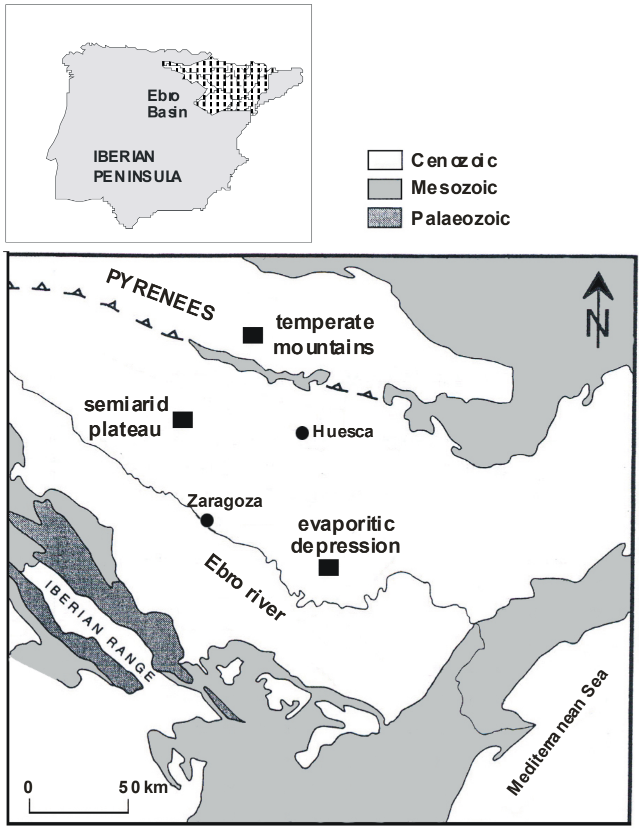

Fig. 1 Location of the study areas in the Ebro basin.

Table 1 Main climatic and land characteristics of the study sites.

Climate	Site	Landscape	Altitude (m)	Vegetation	Rainfall (mm)	Slope (%)	Parent material
Temperate	Aisa-Borau	Middle height mountain	1000–1100	Shrubs, matorral, pines	900–1100	>30	Sandstones, marls
Semiarid	Valareña	Plateaux	360–480	Shrubs, cereals	400–450	2–20	Marls, limestones
Arid	Bujaraloz	Depression	310–340	Shrubs, cereals, fallow	<250	0–5	Gypsum, halite marls

Table 2 Soil characteristics of the study sites.

Studied area	Soil types	pH	OM (%)	CO_3^- (%)	Gypsum (%)	Textural class
Temperate	Kastanozems,	8.1	3.7	35	0	Silt loam
	Cambisols	8.4	2.6	32	0	Silt loam
Semiarid	Regosols	8.7	3.0	40	0	Loam
	Calcisols	8.7	1.3	55	0	Clay loam
Arid	Solonchaks	9.1	1.4	25	34	Silty clay loam

METHODS

In the selected study areas (Fig. 1), sampling sites were chosen to be representative of the main characteristics in terms of land use (cultivated or not), vegetation cover (fallow, shrubs, forest), topography (different positions on the slopes and gradients) and slope orientation. Samples were collected using a motorized percussion corer (8 cm diameter) and the cores were sectioned in depth increments to examine the radiocaesium depth profile. Samples were collected at stable control sites to establish the reference inventories for the study areas.

The methodology for ^{137}Cs analysis is well described in the literature (e.g. Walling & Quine, 1991). Samples were air dried and ground to pass a 2 mm sieve. Measurements of ^{137}Cs activities in soil samples were made by gamma spectrometry (661.6 keV). Counting times were approx. 30000 s and the analytical precision of the measurements was approximately ±6%.

Soil textural classes were defined after grain size analysis using a laser granulometer, and standard soil analyses for pH, and organic matter, carbonate and gypsum content were undertaken (Guitian & Carballas, 1976).

RESULTS

Distinctive ^{137}Cs depth profiles are found in the study areas (Fig. 2). The concentration of the radioisotope is highest in the upper part of the profiles and decreases exponentially with depth at stable sites. In accordance with its higher rainfall, the temperate mountain site has ^{137}Cs values that are almost double those found at stable sites in the semiarid area. In addition, the depth of the profile is greater (around 45 cm), whereas in the arid and semiarid areas radiocaesium is not found at depths greater than 30 cm. Cultivation causes mixing of the plough layer and of the ^{137}Cs profile, and in cultivated areas the soil is commonly thoroughly mixed throughout an extended depth profile that may exceed 40 cm in depth.

The soil redistribution patterns in the study areas are characterized by different degrees of variability. Figure 3 uses box and whisker plots to show the percentage deviation of ^{137}Cs inventories from the corresponding ^{137}Cs reference inventories for the study areas. The large deviations in the semiarid area reflects a greater variability of erosion and aggradation at the sampled sites, although there is a prevalence of erosion. A similar situation is found in the temperate area, although the values of percentage ^{137}Cs loss and the standard deviation values are lower. The largest mean losses of ^{137}Cs are found in the arid area where erosion predominates.

The central depression underlain by evaporites is almost level, but in spite of its flat landscape the ^{137}Cs levels are highly depleted and therefore indicative of severe erosion. In this steppe area the main factor promoting erosion is the lack of vegetation. In addition, wind erosion is also important and the detached particles are in general transported out of the depression and deposition only occurs in a few protected areas, where particles are trapped by the saline vegetation or accumulate under small scarps.

In the semiarid area, marls and limestones form the landscape of the Tertiary plateaux, where the ^{137}Cs data indicate that erosion mainly affects the slopes that are sparsely vegetated, because, in general, the shrub cover protects the soil surface (Quine *et al.*, 1994). The eroded particles transported downslope accumulate on the valley floors, where cultivation, even on gentle slopes, is the main cause of erosion.

The effects of land use on soil redistribution differ between the three study areas. The highest deviations from the reference inventories occur within the cultivated land

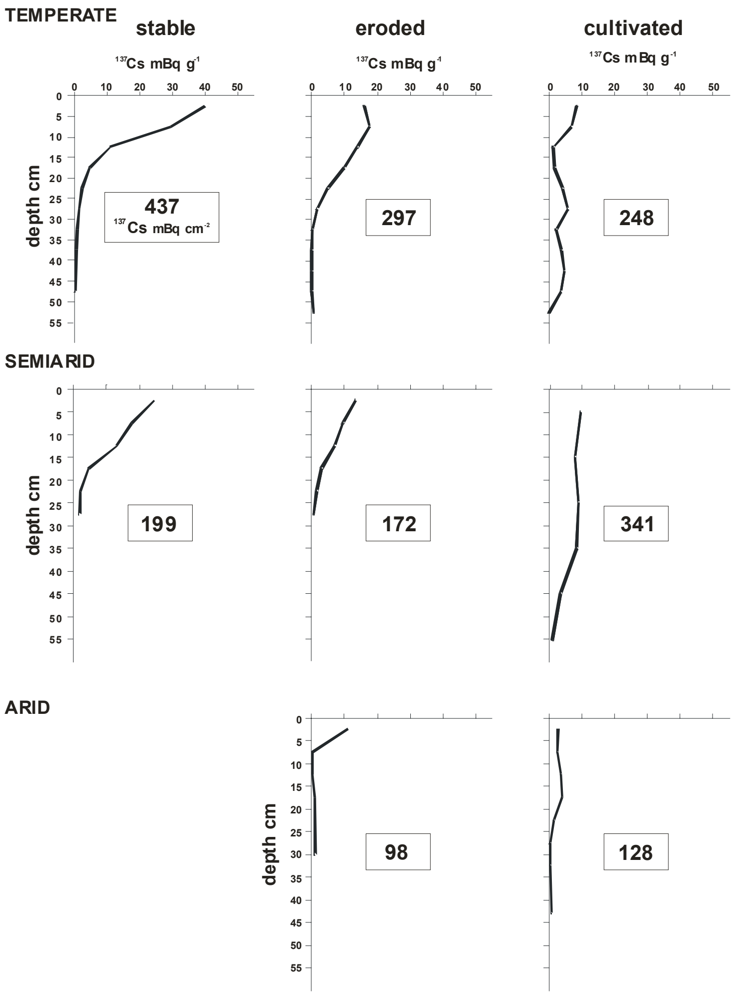

Fig. 2 Caesium-137 profiles and inventories found in stable, eroded and cultivated sites of the study areas.

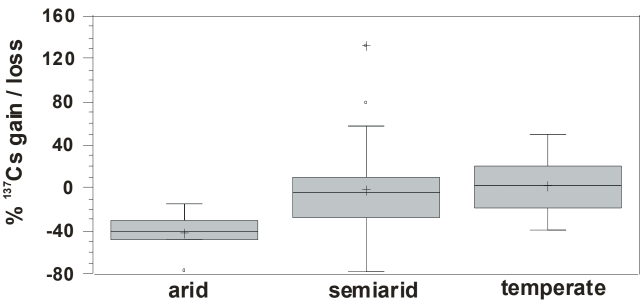

Fig. 3 Box and whisker plots of the percentages of ^{137}Cs gain/loss in the study areas.

of all areas (Fig. 4). Both the largest erosion and aggradation are found in the semiarid area. Deviations of the ^{137}Cs inventories from the reference inventory are lower in the temperate area, but erosion is also important. This is may be due to the fact that cultivated fields in the mountains are on higher slopes than in the semiarid plateau. In the sampled arid area only erosion has been found. The uncultivated land is character-

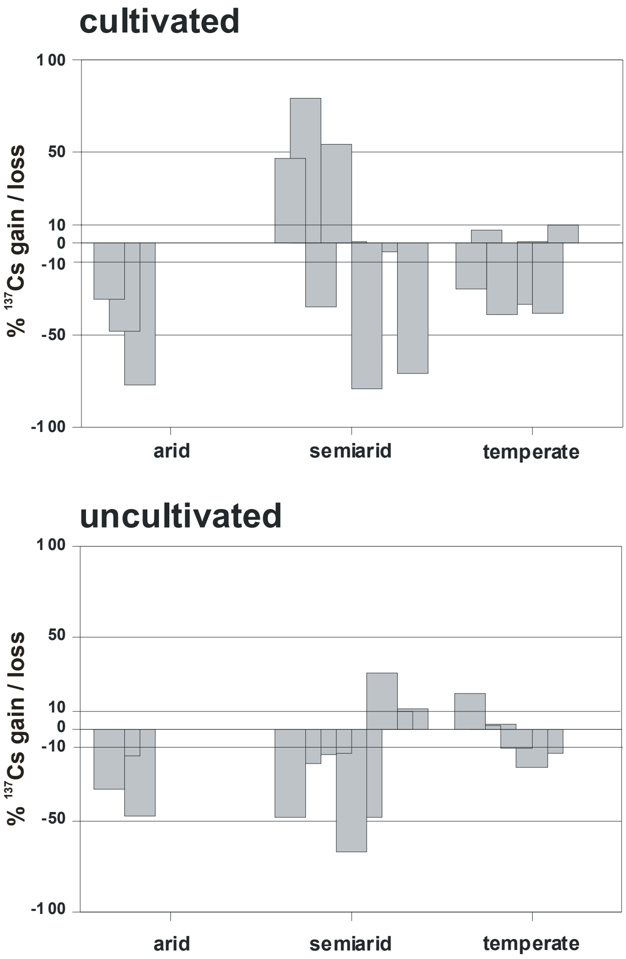

Fig. 4 Percentages of ^{137}Cs gain/loss found in cultivated and uncultivated sites of the study areas.

ized by smaller deviations of the ^{137}Cs inventories from the reference inventories. This suggests that in both the arid and semiarid areas the soil surface is in some way protected by the vegetation cover. This protection is higher in the temperate area, where the ^{137}Cs deviations from the reference inventory are mostly within the confidence interval of the reference value. Therefore little erosion or aggradation occurs in the middle mountain sites that maintain a natural vegetation cover.

In the cultivated sites of the semiarid and temperate areas the effect of the slope has been analysed by comparing the values of the ^{137}Cs deviations from the reference inventory for different slope values. As can be seen in Table 3, for the same difference in the slope gradient (3%), the highest deviations from stability occur in the semiarid area. This confirms the results presented by Quine *et al.* (1994) and Navas *et al*. (1997) that emphasized the key role of cultivation in triggering soil erosion in such environments. In spite of the fact that the temperate mountain fields are on higher slopes, cultivation appears to have less effect on soil loss. This is may be due to the more rapid revegetation of the fields after they are left fallow, so that the soil is promptly protected from intense rainfall events which are frequent during summer in this environment. Nevertheless, in the semiarid area, climate restricts the growth of natural vegetation that otherwise could cover the soil after cultivation.

Table 3 Percentage deviations from the reference inventories in sampled sites of cultivated fields of semiarid and temperate areas.

		% ^{137}Cs gain/loss				
	Slope (%)	Sites				
Temperate	12	–16	–2	–23	–20	3
	15	46	79	–35	54	1
Semiarid	2	–34	–35	20	–34	
	5	–79	–5	–133	–71	

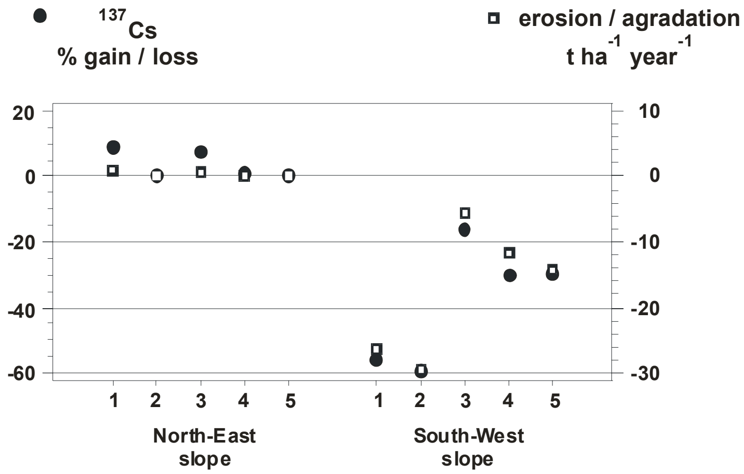

Fig. 5 Rates of erosion and aggradation and percentages of ^{137}Cs gain/loss in slopes with different orientation in the mountain temperate study area.

In the temperate mountains, which lie at the border of the basin, the steep slopes are in a quite stable condition, as indicated by the ^{137}Cs inventories, which are similar to the reference inventory for the area, because of the dense forest cover (Navas *et al*., 2005). In contrast, the cultivated and abandoned lands with south facing slope orientations, are sparsely vegetated by the “matorral” and suffer high erosion. Figure 5 depicts the differences in erosion rates that have been estimated from the calibration of ^{137}Cs data (Soto & Navas, 2004). Although strong differences in the cover density, as a function of slope orientation, are a common feature in the Mediterranean environment, this effect is especially marked in this part of the Pyrenean region. This environment suffered intense land abandonment in the past century. As previous land uses were preferentially located on south facing slopes, the natural recovery of the vegetation has progressed very slowly, because the soils of the intensively cultivated old fields have very low nutrient contents. Therefore soil erosion is noticeably stronger on these south facing fields. Eroded particles follow the normal pattern and accumulate at the footslopes, but important fluxes of sediments reach the watercourses and cause the siltation of reservoirs (Navas *et al*., 1998). Hence, the indirect effects of soil erosion are a major environmental concern in the south Pyrenean region, that contains most of the reservoirs in the Ebro basin, because, the high siltation rates threaten the sustainability of water resources (Valero *et al*., 1999).

CONCLUSIONS

The dynamics of sediment movement are very intense in the central Ebro basin and as a result there are many negative impacts on both soil and water. Vegetation, slope and land use play different roles in the study areas, and they have to be taken into account when assessing soil redistribution in regions with diverse environments. These case studies provide evidence of the contrasts in erosion and sedimentation that can be found in Mediterranean areas. Consideration of this variability is recommended for implementing rational land management practices aimed to preserve soil and water resources.

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