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Using $^{210}Pb_{ex}$ measurements to quantify soil redistribution along two complex toposequences in Mediterranean agroecosystems, northern Spain

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ABSTRACT

Information on soil redistribution rates associated with the intricate patterns of Mediterranean agroecosystems is a key requirement for assessing both soil degradation, and off-site sediment problems that can affect downstream water bodies. Excess lead-210 ($^{210}Pb_{ex}$) measurements provide a very effective means of documenting spatial patterns of rates of soil redistribution in different landscapes, but to date the approach has not been widely used in mountain Mediterranean landscapes. This research aims to use $^{210}Pb_{ex}$ measurements to estimate soil redistribution rates on slopes uncultivated and under cultivation, within two complex toposequences located in the vicinity of Estaña Lake, characterized by an intricate mosaic of land use, steep slopes and anthropogenic modification (e.g. terraces and tracks), which are typical of these agroecosystems in northeastern Spain. A perceptual model is developed to account for the soil redistribution dynamics along both toposequences. This provides a simple and novel methodology adapted to Mediterranean agroecosystems, which besides using information on soil redistribution rates provided by $^{210}Pb_{ex}$ measurements, also takes into account variations in land use and the presence of linear landscape elements, which modify runoff and soil redistribution processes and sediment connectivity along the toposequences. The results show that erosion predominated on the steep cultivated slopes, but lower soil redistribution rates were found on the uncultivated slopes. On the flat areas at the bottom of both transects, deposition was dominant. Variations in land use and the presence of linear landscape elements control soil redistribution processes. Such elements can perform the role of Ecological Focus Areas (EFAs), proposed within 'The Green' Common Agricultural Policy for 2014, in which at least 7% of a farmer's land should comprise EFAs, which can include terraces, landscape features, buffer strips and afforested areas.

1. Introduction

Soil degradation by water erosion represents one of the major environmental problems facing the sustainable management of soil and soil productivity. Cultivation is seen as a key factor promoting soil mobilization and soil loss. Other related effects, including the mobilization and transport of sediment-associated contaminants (pesticides, fertilizers) and the siltation of wetland areas must also be taken into account to protect fragile agroecosystems. In addition, soil erosion transfers soil organic carbon from topsoil to deposition sinks in the landscape and promotes soil carbon replacement at eroded sites (Ritchie and McCarty, 2003).

Increased awareness of the problems of soil loss in the last decade has promoted actions to conserve soil under the European Common Agricultural Policy (CAP), including the most recent Green Areas initiative. In Mediterranean mountain agroecosystems large areas of agricultural land were abandoned during the past century as a result of major socio-economic changes. In recent years, however, some steep marginal lands have been returned to cultivation under the European Agrarian Policy (García-Ruiz et al., 2008; García-Ruiz, 2010; Gaspar et al., 2013). The study area selected for this research is a good example of mountain areas in northern Spain, which illustrates many of the problems associated with steep slopes, high rainfall intensity, changes of land use, and especially the abandonment of the less productive land located on steep slopes. Previous studies highlight the importance of soil erosion in the study area, especially in cultivated areas. For cropland areas, Navas et al. (2012a) used caesium-137 (^{137}Cs)

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measurements to estimate erosion rates as high as 108 Mg ha^{-1} $year^{-1}$, while López-Vicente and Navas (2010) predicted severe erosion rates (>100 Mg ha^{-1} $year^{-1}$), using a combination of the RMMD and SED models, in gullies on Keuper facies. In the study area, the term 'uncultivated' has been used to refer to a range of conditions including areas of undisturbed natural vegetation and areas under Mediterranean forest and scrub, as well as old abandoned fields in long-term fallow (>100 years), which are now covered by dense scrub, and the more recently abandoned fields (ca. 50 years) that have a much reduced vegetation cover. This leads to the development of a spatial pattern of vegetated patches and bare cultivated inter-patch areas, affecting water redistribution and it is well established that vegetation development and vegetation structure affect the connectivity of runoff and soil redistribution processes on slopes (Cerdà, 1997).

Lead-210 (^{210}Pb) is a natural geogenic radioisotope (half life, 22.2 years) of the uranium decay series. Decay of radium-226 in the soil and regolith releases radon-222 (^{222}Rn), which in turn decays to ^{210}Pb. Some of the ^{222}Rn diffuses upward through the soil and enters the atmosphere where it decays to ^{210}Pb and is returned to the earth's surface as fallout. Fallout ^{210}Pb reaching the soil surface is rapidly adsorbed by clay minerals and organic matter, and its subsequent redistribution is controlled by soil redistribution processes in a manner similar to ^{137}Cs (Walling and He, 1999a,b). This fallout ^{210}Pb is termed unsupported or excess ^{210}Pb ($^{210}Pb_{ex}$), since it is not in equilibrium with its parent ^{226}Ra. $^{210}Pb_{ex}$, like ^{137}Cs, offers the potential for use as a tracer in estimating rates of soil redistribution. However, $^{210}Pb_{ex}$ measurements have been less widely used for estimating soil redistribution rates than ^{137}Cs, although their use has increased significantly in recent years (e.g. Wallbrink and Murray, 1993; Walling and Quine, 1995; He and Walling, 1996; Zhang et al., 2006; Kato et al., 2010; Porto and Walling, 2012; Benmansour et al., 2013).

The continuous input of $^{210}Pb_{ex}$ fallout through time means that the contemporary $^{210}Pb_{ex}$ inventory in the soil will reflect soil redistribution and thus loss and gain of $^{210}Pb_{ex}$ occurring within a period equivalent to four times the half-life, and thus the past 100 years (Walling et al., 2003). However, the effect of past changes in the $^{210}Pb_{ex}$ inventory, caused by erosion and deposition, on the contemporary inventory, will progressively decline as the period of time elapsed increases and this must be taken into account when interpreting the impact of the erosional history of a study site on the magnitude of the contemporary $^{210}Pb_{ex}$ inventory. This inventory will clearly be more sensitive to recent soil redistribution, and the estimate of the mean rate of soil redistribution for the past ca. 100 years provided by the conversion model used to estimate the soil redistribution rate from a comparison of the inventory measured at a sampling point with the local reference inventory is likely to be biased towards the recent erosional history of the study site.

In order to understand soil redistribution dynamics in the intricate toposequences that are characteristic of the typical agroecosystems of northern Spain, it is important to know how the interfacing of patches of different land use and linear landscape elements modify soil redistribution processes and the sediment connectivity along the slopes. The use of $^{210}Pb_{ex}$ measurements provides a means of investigating such systems. Their use to investigate both cultivated and uncultivated soils and to quantify sediment sources and sinks along slopes of different aspect represents a novel application, particularly within a mountain agricultural area. The use of $^{210}Pb_{ex}$ measurements to document soil redistribution rates and analysis of the factors that affect soil redistribution along toposequences of different aspect affords a means of developing an improved understanding of the role of land use, soil type and slope gradient in Mediterranean agroecosystems. Additionally, the development of a perceptual model of soil movement of redistribution rates, which take into account changes in land uses and the presence of linear landscape elements, is seen as potentially offering a new tool to elucidate sediment connectivity in intricate landscapes. This is of importance for developing 'green' agricultural practices, as 'The Green' CAP proposes that at least 7% of farmland should be converted to Ecological Focus Areas.

The objectives of this study were therefore to use $^{210}Pb_{ex}$ measurements to estimate the long-term mean annual rate of soil redistribution on cultivated and uncultivated soils along two slope transects representatives of Mediterranean agroecosystems in NE of Spain. Its results aim to contribute to a better understanding of the impact of land use and the presence of linear landscape elements (both natural features and anthropogenic infrastructure) on soil redistribution processes along toposequences. Additionally, assessment of the importance of natural features for trapping and storing eroded soil, as promoted by the new Common Agricultural Policy (CAP) is a key requirement for both the sustainable management of the soil resource and the protection of downstream aquatic ecosystems from degradation resulting from increased sediment loads. Finally, the development of a perceptual model of soil movement aims to elucidate how linear landscape elements contribute to patterns of soil redistribution along cultivated and uncultivated toposequences.

2. Materials and methods

2.1. Study area

The study was conducted along two representative toposequences located in the Spanish central Pre-Pyrenees (NE Spain), close to the northern boundary of the Ebro river basin (Fig. 1). This area includes a freshwater lake. Estaña Lake, in the lower part of the landscape that has been under regional protection since 1997 and is included in the European NATURA 2000 network as a Site of Community Importance. The average annual precipitation is 595 mm (1997–2006) with two wet periods, spring and autumn, and a dry summer with high intensity rainfall events extending from July to October. The average annual temperature is 12.2 °C, with thermal inversions common during the winter (López-Vicente et al., 2008). The Mediterranean agroecosystem of the study area comprises an intricate landscape, characterized by abrupt relief with slope gradients up to 34%. The cultivated and uncultivated areas are heterogeneously distributed. The cultivated fields are located in the lower and mid slope areas and are separated by vegetation strips, while uncultivated areas predominate on the steep slopes. Winter barley is the main crop and, as indicated above, uncultivated areas include areas of Mediterranean forest, scrubland and abandoned fields recolonised by natural vegetation. The predominant soil types along the toposequences are stony Calcisols and Regosols. Leptosols are restricted to the upper part of the slope under Mediterranean forest underlain by Muschelkalk facies, and Gypsisols cultivated for cereals are restricted to the lower part of one of the transects underlain by Keuper facies.

Two representative hillslope transects, extending from the divide to the lake, were selected to represent different toposequences within this agroecosystem (Fig. 1). A total of 34 sampling sites, approximately 50 m apart were established along both transects. However, it was recognised that tillage erosion in fields delimited by furrows and tracks can cause significant soil redistribution both at the head and the bottom of the fields (Gaspar, 2011), and thus the spacing of the sampling sites on the lower cultivated part of the ST was reduced to 25 m, in order to provide a reliable representation of soil redistribution in this area (Fig. 1).