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The influence of catchment morphology, lithology and land use on soil organic carbon export in a Mediterranean mountain region

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ABSTRACT

Soil erosion processes play an important role in the redistribution of soil organic carbon over the landscape. The factors controlling this carbon (C) redistribution have been thoroughly studied at the plot scale, but knowledge at the landscape level is still limited. In this study, we explore the role of different factors on C export at the catchment scale. We measured the C concentration in sediment deposited behind check-dams at the outlet of catchments ranging between 7 ha and 438 ha and combined it with specific sediment yield rates (SSY, Mg ha^{-1} y^{-1}) to estimate catchment specific C yields (SCY, g m^{-2} y^{-1}). Correlation analysis between C concentration, SCY and morphological, lithological and land use data derived from GIS analysis and interpretation of ortophotoimages was conducted. The results showed a close relationship between SCY rates and catchment morphometric properties such as catchment area, slope gradient and lithology, while C concentration in sediments was correlated to the percentage of forest cover in a catchment. In addition, it is suggested that morphological properties such as average slope gradient, drainage area and drainage density could have implications for the fate and stability of C stored at depositional sites through changes in the in-depth variability of C concentration in sediments and in the concentration of two measured C fractions. Further research is needed in this direction.

1. Introduction

Soil organic carbon redistribution by soil erosion processes and its transport into the aquatic system can play a significant role in the biogeochemical cycling of carbon (C) (Battin et al., 2009; Berhe et al., 2007; Quinton et al., 2010; Stallard, 1998). Recent estimates of organic C loads transported and buried with sediments in large rivers have stressed the importance of catchment-derived C fluxes in total C budgets (Ran et al., 2014; Aufdenkampe et al., 2011). However, since only a very small percentage of eroded C is exported from catchments (Chaplot et al., 2005; Smith et al., 2005), the re-mobilization (continuous detachment and deposition) of eroded C (Rumpel et al., 2014) and the environmental conditions (e.g. temperature, humidity) during transport and deposition within catchment boundaries will have a strong impact on its fate (Gregorich et al., 1998).

Understanding changes in the fate of eroded soil organic carbon during the erosion process demands for increased knowledge on the factors involved along its different phases of detachment, transport and deposition. Over the last decades, several studies have shown how C export from soils and its concentration in sediments depend on a number of factors, including: rainfall characteristics, soil texture, slope gradient and length, geomorphological factors or land use and management (e.g. Owens et al., 2002; Polyakov and Lal, 2004; Schiettecatte et al., 2008). Nevertheless, most of these studies have been plot-based, considering the controlling factors separately and focused mainly on interill erosion, thus limiting their applicability at the catchment scale where a large number of factors and erosion processes interact.

More recently, and fulfilling the need of broader scale studies and quantification of catchment scale C budgets, a shift from plot to full slope or catchment scale approaches has been observed. These new studies identified topography, and consequently geomorphic processes (e.g. Chaplot et al., 2010; Guo et al., 2010; Hoffmann et al., 2014; Yoo et al., 2006) as well as differences in the stability of SOC between landform positions (Berhe et al., 2008; Chaplot and Poesen, 2012; Doetterl et al., 2012; Hancock et al., 2010) as important variables to explain soil organic carbon (SOC) spatial distribution. In addition, it has also been reported how changes in land cover can modify the amount of C exported by erosion by changing SOC stocks at source sites by changing potential runoff rates (Chaplot et al., 2009; Molina et al., 2007; Sitaula et al., 2004; Thothong et al., 2011). Despite an increase in the number of landscape scale studies, many aspects of how transport and selectivity during the redistribution of SOC may affect carbon dynamics are unknown (Kirkels et al., 2014) and it is still difficult to find studies that integrate and assess the effect of multiple factors potentially controlling C redistribution at the landscape level.

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From a hydrological and geomorphological perspective, the transport of particulate (non-dissolved) C particles has been described to closely follow sediment dynamics (Starr et al., 2000). Therefore, like sediment, C redistribution can be expected to be influenced by lithology (Bellin et al., 2011; Romero-Diaz et al., 2007), land use type and pattern (Fiener et al., 2011; Van Rompaey et al., 2002), topography (Romero-Diaz et al., 2007), and sediment connectivity (Sougnez et al., 2011). In addition, the immediate fate of transported C, whether deposited close to the source soil or exported to the aquatic system, will depend on the size and stability of the transported aggregates (Starr et al., 2000). Notwithstanding, organic particles may also behave differently than mineral particles due to their inherent characteristics (Walling, 1983), being affected by additional processes that can alter the C concentration and characteristics in sediments. For instance, the loss of C through mineralization during transport or after deposition (Lal, 2003), the proportion of fractions of C with different turnover rates and its transformation along the landscape (Berhe and Kleber, 2013; Rumpel et al., 2014), changes physical and chemical protection mechanisms of eroded particles (Berhe et al., 2008; Doetterl et al., 2012; Wang et al., 2014) and also the accumulation of C in deposited sediments through the input of autochthonous organic matter (Stallard, 1998).

The transfer of C from soils to streams and catchment boundaries is, therefore, complex and the few studies that have investigated the relationships between C export and different factors at the catchment scale have mainly focused on dissolved or suspended C in agricultural catchments and their relationship with hydrological catchment properties (Oeurng et al., 2011). In the Mediterranean region, where high soil erosion rates reduce the fertility of soils with already low SOC concentrations (Cantón et al., 2012), very little emphasis has been placed on the study and quantification of the catchment scale transport and export of eroded C. Increased knowledge on its controlling factors could help in the development of more precise numerical models and improve catchment management to preserve soil fertility and avoid large C exports into the aquatic system. Against this background, the objective of this study is to explore the relationships between a range of catchment properties (morphometric, soils, lithology and land use) and the C concentration in sediments and catchment scale C export by soil erosion processes.

2. Materials and methods

2.1. Site description

The study was conducted in a 50 km^2 watershed located within the province of Murcia, SE Spain (Fig. 1). The average altitude of the study area is 1403 m and it is characterized by a dry–subhumid Mediterranean climate, belonging to the supramediterranean bioclimatic zone. Mean annual precipitation and temperature are 583 mm and 13.3 °C respectively (Boix-Fayos et al., 2007). Lithology is spatially heterogeneous and consists mainly of limestone, marls and sandstone from the Mesozoic and Cenozoic (IGME, 1978). Dolomites and limestones occupy the highest elevations in the catchment, often visible in the form of small cliffs, while more marls and sandstones are found in the highly dissected valley floors. While dolomites and limestones are considered hard erosion resistant lithologies, marls and sandstones are unconsolidated erodible material (Romero-Díaz, 2003). Soils are mainly classified as Calcaric Regosols and Calcaric Lithosols, although Cambisols and Mollisols can also be found in certain slopes under forest cover (Alías et al., 1991). Vegetation consists of a mixture of conifer forests, shrubland, pastures and dryland agriculture (Fig. 2). Rills and gullies are common features on both agricultural and naturally vegetated hillslopes, while bank and channel erosion are active along the whole drainage network. To address the problems arising from on-site and off-site effects of soil erosion, the regional Government promoted hydrological correction works involving afforestation and the construction of check-dams. The impacts of afforestation, construction of check-dams and land use changes on geomorphological processes and sediment yield in the catchment have been explored in detail in previous works (Boix-Fayos et al., 2007, 2008; Nadeu et al., 2012; Quiñonero-Rubio et al., 2014). These check-dams have divided the catchment into smaller subunits (catchments), 18 of which were used in this study (Fig. 1 and Table 1) with average altitudes ranging between 1146 m and 1714 m.

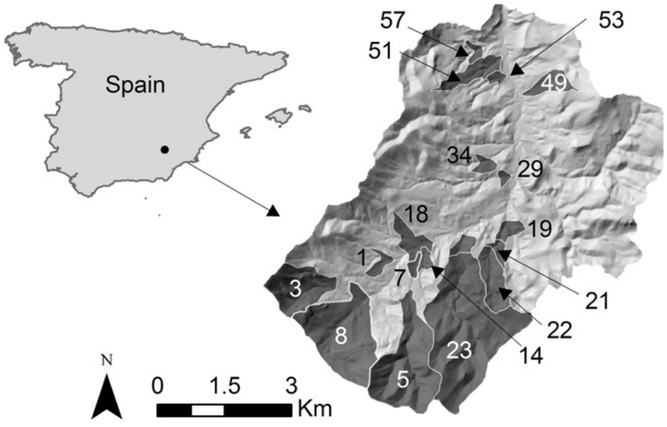

Fig. 1. Map of the study site. Numbers refer to catchment ID's.

2.2. Field sampling

Sediment samples were taken from the sediment wedges created behind each check-dam. Sediment deposition at these sites is often event-based (Boix-Fayos et al., 2008) and size dependent; with a large fraction of fine particles reaching the front of the wedge and coarser particles mainly settling at the back (Nadeu et al., 2012). Deposition in the sediment wedges can be regarded as a mixture of suspended sediment (mostly reaching the front of the wedge) and bedload transported sediment (preferably deposited in the back) (Nadeu et al., 2012). For this study, sediments were sampled at the front of the wedge, assuming them to be representative of potentially exported sediment out of the catchment during the study period. The sediment wedges were dry at the time of sampling, and only become saturated and temporarily covered by a shallow water later after rainfall events lasting over several days, a situation which occurs very seldom throughout the year during autumn and spring. An auger was used to sample in depth in 5 cm increments until bedrock was reached with an average of 84 ± 7 cm and a maximum of 150 cm in one of the catchments. In addition to the depth profile, two sample replicates were taken in 15 cm increments. Data from total sediment volume for each sediment wedge was taken from a previous study (Boix-Fayos et al., 2008). Soil sampling was carried out on a land-use based strategy, taking samples from at least 2 locations per LULC class (see Section 2.4) and catchment based on the 2008 land use distribution. The topsoil, 0–10 cm, was sampled to characterize the material most likely to be mobilized by soil erosion processes. The sampling of soils and sediments was done during several field campaigns over three years: 2004, 2009 and 2010.

2.3. Soil and sediment analyses

Soil and sediment samples were analyzed for bulk density, particle size distribution (PSD) and total organic carbon content (C). The sediment cores used for bulk density determination were later used for PSD and organic carbon analyses. Therefore, sediment samples were first oven-dried at 60 °C instead of 105 °C to avoid the loss of volatile C fractions (Bates, 1993), weighted, and later sieved at 2 mm to proceed with the rest of analyses. Soil samples were air-dried and sieved at 2 mm while those for bulk density determination were dried at 105 °C and weighted. Particle size distribution was determined through a