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Losses and redistribution of organic carbon by erosion in fragile agricultural and restored catchments

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Abstract

Although large efforts are being made to understand the flow paths of OC at the catchment scale, studies carrying out estimations of redistribution of organic carbon by lateral flows at this scale are still scarce. Particularly little is known on how organic carbon is redistributed on fragile environments with a variety of lithologies, combined land uses (large agricultural areas adjacent to large reforested areas) and ephemeral hydrological and sedimentological pulses, typical of Mediterranean conditions. The objective of this work was to estimate the organic carbon redistributed by lateral flows in representative Mediterranean catchments, highly disturbed by agricultural terraces, land levelling for agriculture, reforestation and construction of check-dams, with erodible lithologies and shallow soils.

A general estimation of total organic carbon redistributed by lateral flows was carried out in two medium sized catchments (2000-5000 ha) in SE Spain, with contrasting climatic conditions (semiarid versus subhumid). Existing data on the mass of sediments behind check-dams, organic carbon concentration of soils and sediments, and spatial information were combined to estimate organic carbon redistributed by erosion processes on both catchments. The results show that sediments had organic carbon concentrations similar to those of agricultural soils but much lower than those of forest and shrubland soils. Overall, a loss of more than 10% of the superficial soil carbon stock can be attributed to erosion processes during studied period (20-30 years), with an annual rate of 0.4% for both studied catchments. It was estimated that between 60-70 % of the organic carbon redistributed by lateral fluxes was redeposited within the fluvial system, with different residence times depending on the fluvial dynamics, and the rest was exported downstream or lost by mineralization. These results point out the need to protect soil organic carbon resources in active fluvial environments of such fragile ecosystems. This can be achieved, for instance, by stabilizing organic carbon in soils and sediments and decreasing connectivity of rich-carbon soils with channels.

Keywords: organic carbon redistribution, lateral fluxes, catchment scale, restored lands, reforestation, check-dams, soil carbon yield.

Introduction, scope and main objectives

Lateral flows of sediment are affected by agricultural management practices and by land use changes (Van Oost et al., 2007; Martinez-Mena et al., 2008; Quijano et al., 2016), which influence runoff production, soil stability, sediment detachment and available SOC in the soil surface, having thus an influence on the SOC detached and transported (Martínez-Mena et al., 2012; Nadeu et al., 2015; Quijano et al., 2016). Multiple experiences at plot and field scales reported selective erosion of fine particles and enrichment of SOC in sediments compared to the original soils (Starr et al., 2000; Martínez-Mena et al., 2012). However, the redistribution of organic carbon by lateral flows at the watershed scale seems to be much more complex with interference of other ecogeomorphological processes (Boix-Fayos et al., 2015).

In addition to the factors and mechanisms mentioned above, redistribution of organic carbon by lateral flows at coarser scales can be affected by fluvial processes, complex erosion patterns (gully, channel and bank erosion) and by transport and post-depositional processes in sediments (Van Hemelryck et al., 2011; Boix-Fayos et al., 2015). The catchment scale research on this matter could identify organic carbon sinks providing insight on opportunities for carbon sequestration through sediments management.

Therefore to close carbon budgets at the catchment scale, it is crucial to understand how organic carbon moves with sediments along fluvial paths (Hoffmann et al., 2013). However, although large efforts are being made to understand the flow paths of OC at the catchment scale, the studies carrying out estimations of global redistribution of organic carbon by lateral flows at this scale are still scarce. Particularly, little is known on how organic carbon is redistributed on fragile environments with a variety of lithologies, combined land uses (large agricultural areas adjacent to large reforested areas) and ephemeral hydrological and sedimentological pulses, typical of Mediterranean conditions. The objective of this work was to estimate the organic carbon redistributed by lateral flows in two representative Mediterranean catchments, highly disturbed by agricultural terraces, land levelling for agriculture, reforestation and construction of check-dams, with erodible lithologies and shallow soils.

Study area and methodology

Research was carried out in two catchments (Cárcavo and Rogativa) in SE Spain, representing medium mountain Mediterranean environments with a variety of land uses, mainly agriculture and reforested land, and different climatic conditions. Both catchments had large extensions dedicated to agriculture in the 1950's (40-50 % of their catchment area), however socioeconomic evolution of the area led to a large abandonment of agricultural activities in the second half of last century. Besides, large reforestation works and hydrological control works were carried out in order to prevent flooding and siltation of water reservoirs downstream of each catchment. Both catchments have experienced a greening up effect in the last decades, due to natural and induced reforestation (>50 % of forest in the drainage area nowadays). The Cárcavo catchment has more arid conditions, with 279 mm of precipitation per year, an extension of 2732 ha, and a lithology of marls, limestones and Quaternary deposits. In the 1980's a net of 36 check-dams was constructed to prevent floods. The Rogativa catchment has subhumid conditions with 530 mm of precipitation per year, a mixed lithology including marls, sandstones and limestone. It has an extension of 4770 ha and in the 1970's a net of 58 check-dams was constructed mainly to prevent siltation of the downstream Taibilla reservoir.

In both areas an extensive research has been carried out in the last decade on land use changes, erosion processes, fluvial dynamics and organic carbon redistribution by lateral fluxes (Boix-Fayos et al., 2007, 2009, 2015; Castillo et al., 2007; Nadeu et al., 2012, 2015; Nadeu, 2013). From this research data bases on different sediment, soil and erosion processes information were available. The research methodology combined fieldwork (sampling sediments at subcatchment level, sampling soils and geomorphological mapping), laboratory analysis (physicochemical characteristics of sediments and soils) and spatial GIS analysis of catchment and subcatchment areas. In this work we use the total sediment masses retained in the check-dam network of both catchments (Castillo et al., 2007; Boix-Fayos et al., 2007), the organic carbon

data of soils and sediments and spatial data extracted for catchment areas (Boix-Fayos et al., 2015 and Boix-Fayos et al., 2017).
We estimated the total organic carbon (TOC) redistributed (TOC_{red}) by lateral flows at the catchment scale both for Cárcavo and Rogativa catchments, recalculating values after Nadeu (2013), and using her same approach, by:

$$TOC_{red} = 0.26 \times TOC_{red} + 0.20 \times TOC_{red} + \sum TOC_{CD} + \sum TOC_{exp}$$

Where 0.26 was extracted from modelling exercises at the subcatchment level in the Rogativa catchment and represents the fraction of sediment that it is redeposited at the hillslopes after initial erosion (Nadeu et al., 2015), 0.20 was extracted from literature review representing the fraction of soil organic carbon that is mineralized during transport and deposition processes (van Hemelryck et al., 2010). TOC_{CD} represents total organic carbon stored in alluvial wedges behind check-dams and TOC_{exp} represents organic carbon exported downstream check-dams, being both estimated from the volume and the density of sediments retained by check-dams and the trap efficiency of those as in Boix-Fayos et al. (2009).

Results

In both catchments, organic carbon concentration of sediments in the fluvial system and stored in alluvial wedges at check-dams is significantly lower than the soil organic carbon concentration of forest and shrubland soils (Table 1). On average, sediments in both catchments contain a 43% of the organic carbon of forest soils (Table 1). However, organic carbon concentration is higher in sediments than in agricultural soils, although without significant differences between both groups. The specific soil carbon yield estimated at the catchment scale is similar for both areas (0.040 tn $ha^{-}1$ yr^{-1} and 0.037 tn $ha^{-}1$ yr^{-1} for Cárcavo and Rogativa catchment, respectively).

Table 1. Indicators of the Total Organic Carbon concentration, stored and exported in the Cárcavo and Rogativa catchments.

Land use pattern	TOC forest soils	TOC agricultural soils	TOC Sediments 0-100 cm	Soil TOC stock	TOC buried check-dams	TOC exported downstream check-dams	Specific soil carbon yield (SCY) catchment
	g kg^{-1}	g kg^{-1}	g kg^{-1}	5 cm tn ha^{-1}	tn	tn	tn ha^{-1} yr^{-1}
Cárcavo 1981	15.2 ± 9.35a	4.4±1.06b	6.6b	7.3	677.65	45.156	0.040±0.047
Rogativa 1974	18.82 ± 5.37a	8.12 ± 3.20b	11.7b	9.31	1654.18	502.29	0.037±0.045

a,b show significant differences between groups of samples according to Kruskal-Wallis test at $p < 0.005$.

Total organic carbon removed by erosion processes represented an 11.37% of the superficial 5 cm soil stock in 21 years for the Cárcavo basin, and a 10.60 % of that for the Rogativa basin in 27 years. The rate of TOC soil loss with respect to the original soil stock was 0.54 % per year in Cárcavo and 0.39 % in Rogativa basin. From the organic carbon redistributed by lateral fluxes, 69% and 61% was redeposited within the fluvial system in Cárcavo and Rogativa, respectively, with different residence times depending on the fluvial dynamics, while the rest was exported downstream or lost by mineralization.

Discussion

The sediments circulating in the Cárcavo and Rogativa fluvial systems are on average impoverished in TOC, when compared to the values reported for eroded sediments obtained at smaller scales in erosion plots (Quinton et al., 2006; Martinez-Mena et al., 2008). This can be explained by the different erosion processes mobilizing sediments at different spatial scales (Boix-Fayos et al., 2009; Nadeu et al., 2012). At the hillslope scale, sediments impoverished in TOC are found occasionally when compared to reference sites, but sediments enriched in TOC are also found due to high burial efficiency (Wang et al., 2015). At the catchment scale, both sediments impoverished in TOC with respect to catchment soils (Boix-Fayos et al., 2015; Ran et al., 2014) and sediments enriched in TOC associated with the suspended load (Rhoton et al., 2006) have been reported. The sources of sediments and how sediments are connected to the fluvial channel and transported seem to have a key role in determining the enrichment or depletion of OC in sediments with respect to the catchment reference soils (Nadeu et al., 2012). The specific carbon yield (or TOC erosion rate) in the studied catchments are lower than the ones reported for humid ecosystems - such as 0.07 Mg ha^{-1} y^{-1} (Smith et al., 2005) and 0.113 Mg ha^{-1} y^{-1} (Izaurralde et al., 2007), but the same to the value (0.04 Mg ha^{-1} y^{-1}) reported by Doetterl et al. (2012) derived from the modelling of eroded pastures worldwide. It is also close to the one reported by Ma et al. (2016) (0.032Mg ha^{-1} y^{-1}), in their study of diverse reforested areas. Those authors considered that reforestation was not an optimal solution of land restoration in their area in terms of soil loss and C sequestration.

Conclusions

In fragile Mediterranean environments with active geomorphological processes, despite restoration activities (reforestation and hydrological control works), erosion processes caused the loss of more than 10% of the superficial soil carbon stock during the studied period (20-30 years). At this catchment scale, sediments flowing within the fluvial system have similar concentrations of organic carbon than agricultural soils of the catchments. Losses of soil organic carbon due only to lateral fluxes represent a rate of at least 0.4% per year in both studied catchments, without taking into account losses of organic carbon due to other processes (as land use conversions and land management practices). Those results point out the need to protect soil organic carbon resources in active fluvial environments of those fragile ecosystems, for instance with measures for stabilizing organic carbon in soils and sediments and decreasing connectivity of rich-carbon soils with fluvial channels.

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