Lateral mobilization of soil carbon induced by runoff along karstic slopes

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Graphical abstract

Highlights

- ¹³⁷Cs inventories document gain or loss of soil by water erosion on karstic slopes
- Perceptual approach illustrates SOC and SIC lateral movement along five transects
- Topography and landscape linear elements affect runoff and sediment pathways
- Erosion-induced SOC loss depends on erosion rates and topsoil SOC content
- SIC patterns depends on pedogenesis besides soil mobilization

Keywords: ^{137}Cs ; Soil organic carbon (SOC); Soil inorganic carbon (SIC); Water erosion; Slope curvature; Landscape linear elements (LLE).

Abstract

Soil erosion induced by runoff is a main hydrological pathway for lateral transport of carbon in terrestrial landscapes. More information about how water erosion influences the carbon gains and losses at different erosional and depositional landform positions is critical, especially in fragile agroecosystems with a variety of land uses and ephemeral hydrological and sedimentological pulses, typical of Mediterranean environments. The purpose of this study is to characterize the lateral mobilization of soil organic and inorganic carbon (SOC and SIC) along topographically driven transects over a period of four decades in a sub-humid karstic area in northern Spain. The ^{137}Cs inventories and the characterization of terrain attributes of the study area were used to identify whether erosional or depositional processes have been predominant in the 58 sampling sites. Average soil losses and gains varied between -4 and $+4 \text{ mm ha}^{-1} \text{ yr}^{-1}$, and the carbon patterns obtained are discussed in the context of the dominant hydrological processes in the study area. Results indicate that SOC and SIC losses were related to an increase in water flow accumulation, while the highest SOC gains were recorded at concave positions. Soil erosion processes and the content of SOC and SIC in soils are the two main factors controlling carbon budgets. The topographical and geomorphological characteristics of the transects, the spatial distribution of land uses and the presence of landscape linear elements such as terraces or paths, affect runoff and determine the sediment connectivity and carbon dynamics along the slopes. The combined use of ^{137}Cs and the perceptual model provides reliable SDR estimates benefiting the appraisals of the

redistribution of eroded carbon. The knowledge of processes involved in the lateral carbon movement induced by runoff along karstic hillslopes provides a better understanding of the role of soil erosion as carbon source or sinks in the global carbon cycle.

1. Introduction

Water erosion is one of the major environmental threats to soil function (Pimentel et al., 1995) reducing its quality and productive capacity by lowering the nutrient-rich upper soil layers (Quijano et al., 2016a; Gaspar et al., 2019). The hydrological route for the lateral transport of soil carbon affects on its storage in the landscape that is the largest carbon pool in the terrestrial biosphere, including the organic (SOC) and the inorganic soil carbon (SIC) (Lal, 2003; Novara et al., 2016). As surface soil horizons contain the greatest carbon contents, most carbon movement is associated with surface runoff as the main transport agent in karstic landscapes with low flow hierarchical organization (Gaspar et al., 2017). Runoff disintegrates soil aggregates and transport carbon associated with the topsoil away from eroded areas (Van Oost et al., 2004; Hua et al., 2016; Quijano et al., 2019). Thus soil erosion has a major impact on soil carbon stocks and its role as a net sink or source of atmospheric CO₂ remains highly debated (Lal, 2003). Moreover, the severity of erosion can substantially increase as natural forest or rangeland is converted to cropland, becoming particularly vulnerable to runoff, especially on steep slopes (Navas et al., 2013) as well as a result of land abandonment (Navas et al., 2017; Lizaga et al., 2019).

Karst regions are characterized by low organization of stream systems resulting in no permanent water courses after the rains (Doglioni et al., 2012). Sheet erosion is the most important direct driver of water erosion in many karstic landscapes. The processes

of sheet and rill erosion involve the soil particles detachment by raindrop impact (Beguería et al., 2015), and subsequent transport of sediments by flow traction, removing most of the fertile topsoil when surface runoff concentrates. Each erosional event removes an increment of soil from the surface, and in many soils this surface increment is richer in soil organic matter than the underlying soil horizons. The processes that redistribute soil and nutrients can vary on local scales due to landscape heterogeneity affecting carbon input and carbon loss rates and resulting in differences in SOC contents along topographic gradients (Doetterl et al., 2016; Fissore et al., 2017; Quijano et al., 2020). Preferential removal of SOC from upslope sites by runoff increases organic carbon content in sediments that are usually rich in fine silt and clay-size particles (Martínez-Mena et al., 2012).

The spatial variability of soil organic (SOC) and inorganic carbon (SIC) can be affected by environmental factors such as vegetation cover, topography characteristics, soil management practices and soil redistribution processes (Navas et al., 2008). In addition, land use results in elimination of vegetation cover, causing increasing soil exposure to rainfall impact (Ramos et al., 2019) and hence increases erodibility of soil and carbon removal.

The lateral movement of SOC shows similar spatial patterns with that of soil erosion and the combined use of the radiotracer ^{137}Cs and terrain attributes information allow identifying whether erosional or depositional processes are related to nutrients patterns (Mabit and Bernard, 1998; Mabit et al., 2008; Navas et al., 2011 and 2012; Young et al., 2014; Quijano *et al.*, 2016b; Gaspar *et al.*, 2013a and 2019). Recently, some additional studies (e.g. Yue et al., 2016) have confirmed the significance of lateral soil carbon transport by erosion processes in the global carbon cycle and have highlighted the

importance of reducing uncertainty in assessing the terrestrial carbon balance due to soil erosion.

Awareness of the distribution and magnitude of land carbon mobilization is important both for improving models of the carbon cycle (Quijano et al., 2017) and for management practices aimed to preserve carbon stocks and enhance carbon sinks (Yue et al., 2016). Correspondingly, there is a need to consider the global significance of soil erosion from soil organic carbon cycling schemes (Chappell et al., 2016). For this reason, the movement of carbon, organic and inorganic, during erosion processes should be elucidated.

To gain knowledge on the lateral movement of organic and inorganic carbon that is still not fully understood it is of utmost importance to quantify the amount of SOC and SIC that is mobilized along karstic slopes for improving soil conservation strategies in agroecosystems. To address this gap, our study aims to estimate the soil and carbon redistribution induced by water erosion during a 40 years period in a karstic agroforestry mountain ecosystem located in northern Spain. To this purpose, we established in the Estaña catchment five topographically driven transects with mixed land uses to: i) assess what factors modify the runoff patterns with impact on soil redistribution and ii) evaluate the mobilization of topsoil organic and inorganic carbon and the soil carbon balance along the transects.

2. Material and Methods

2.1. Study area

The study was conducted along five representative transects located around the *Estanque Grande de Abajo* Lake near Estaña, in the north part of Spain (Fig. 1). This is a karstic area with abrupt topography and an intricate mosaic of land uses representative of

Mediterranean mountain agrosystems, composed by winter barley as the main crop for cultivated sites, and forest and scrublands for uncultivated sites. Gentle slopes are preferably located in low altitudes areas surrounding the two collapse dolines where a lake is situated. Altitude ranges from 679 m to 892 m in the northern headwater area of the 1.3 km² study catchment receiving mean annual rainfall of 595 mm with mean temperature of 12°C (Gaspar and Navas, 2013). There are no permanent rivers in the catchment and the only active erosional features are rills and gullies generated by surface water flows after rainfall events. The complex relief, the singularity of morphological landforms and other landscape linear elements (LLE) like terraces, paths and vegetation strips, define the characteristics of the drainage system (Fig. 1).

A detailed analysis of the main runoff pathways within the study catchment was obtained by creating a reclassified Strahler's order map (Fig. 1) using the *Stream Order-Strahler* tool of the Hydrotools 1.0 extension in ArcGIS 10.0 (Schäuble et al., 2008). Stream Order-Strahler tool has been used in recent years for hydrological characterization (Pandey et al., 2010) and for improving soil redistribution calculations within catchments (Mourier et al., 2008). A reliable digital elevation model (5m, cell size) (Navas et al., 2014) and the LLE's map elaborated with coloured orthophotos and field surveys, were used to calculate the flow direction and flow accumulation maps taking into account the LLE that modify and interrupt the hydrological connectivity of the flows (Borselli et al., 2008; Lizaga et al., 2018).

2.2. Experimental design and analyses

From the catchment divides to the central lake five transects (T1 to T5) with different ranges of altitude, orientation and lengths were established for sampling. A total of 58 soil profiles located 50 m apart retrieved in a previous research (Gaspar and Navas 2013)

were used to quantify soil redistribution rates. The cm-sectioned profiles extended from 10-55 cm depending on the soil type in each sampling site (Gaspar et al., 2014). In each soil profile topsoil samples (0-5 cm depth) were collected, obtaining 4, 7, 12, 13 and 22 samples for transects T1, T2, T3, T4 and T5, respectively, depending on the transect length, to relate to ^{137}Cs soil redistribution estimates.

Samples were air-dried, gently disaggregated, and sieved to 2 mm before the analyses. The SOC content was determined by wet dichromate oxidation method and subsequent titration with ferrous ammonium sulphate using a Mettler Toledo titrimeter with a selective electrode. The percentage of SOC was obtained by using the conventional factor 1.724 (Mattingly, 1974), based on the assumption that soil organic matter contains 58% carbon. Calcium carbonates were measured using a Barahona pressure calcimeter, and the percentage of SIC was estimated from stoichiometry.

Each profile was composed of several sectioned intervals that retained the whole ^{137}Cs profile to compare with the reference inventory for the area and estimate soil erosion rates by applying appropriate mass balance conversion models (Soto and Navas 2004, 2008). The ^{137}Cs derived soil redistribution rates were estimated from existing ^{137}Cs inventories (Gaspar and Navas, 2013) and the average thickness of soil lost or gained (mm) was obtained for each sampling site. The SOC and SIC contents (%) were converted into contents per surface area expressed as inventories or stocks (kg m^{-2}) multiplying the content by the mass of the fine fraction and dividing by the surface of the core sampler. Taking into account the thickness range of soil lost or gained ($\text{mm ha}^{-1} \text{ yr}^{-1}$) in each sampling site we derived an average value of carbon loss or gain ($\text{Mg ha}^{-1} \text{ yr}^{-1}$) over the 40 years study period based on the percentage of SOC and SIC estimated from the topsoil samples (equation 1). Our approach relied on erosion-induced carbon mobilization and the assumption that SOC and SIC content was temporally constant.

$$C_{l/g} = C_c * BD * D * 100 \quad (1)$$

where $C_{l/g}$ is the carbon loss or gain in each point ($Mg\ ha^{-1}\ yr^{-1}$); C_c is the content of SOC or SIC (%) in the 0-5 cm topsoil sample; BD is the bulk density of the sample ($g\ cm^{-3}$); D is the average thickness of soil lost or gained (m) at the sampling site estimated by ^{137}Cs .

Statistical analyses were performed using Statgraphics Centurion XV, including ANOVA tests, regression analyses and normality test.

2.3. Perceptual model for estimating soil and carbon redistribution

The thickness loss or gain of soil and the related SOC and SIC for each profile was extrapolated along the hillslope by using a perceptual model, assuming that each transect represents a 1 m wide strip. The point data were prolonged to individual segments extending halfway to the adjacent points in each direction, following the methodology proposed by Collins et al. (2001) and Walling et al. (2001). This approach was modified by Gaspar et al. (2013b) to adapt it to the characteristics of typical Mediterranean mountain agroecosystems, in order to take into account changes in land use, curvature of the slope and presence of linear landscape elements. This was achieved by relating the segment length to similar vegetation cover in the absence of LLE, which cause changes in the segment lengths if it is needed.

In order to obtain sediment budgets for different sections along the transects, the resulting areal estimates provided information on the total (gross) soil loss ($kg\ yr^{-1}$), total (gross) soil gain ($kg\ yr^{-1}$), net soil loss ($kg\ yr^{-1}$) and the sediment delivery ratio (%). Similarly, SOC and SIC budgets were established. When any LLE interrupts the sediment connectivity along the transect, specific sections were defined by integrating several segments. In addition, the presence of hills or a rock outcrop divides the transects into

two parts, above and below the inflexion. The first part is defined from the head of each transect to the maximum convexity, while the second part is limited from the convex point to the bottom slope at the edge of the lake.

3. Results

3.1. Soil and carbon loss and gain

The studied topsoils were alkaline (mean pH = 8.3), had low salinity (mean EC = 0.4 dS m⁻¹), moderate gypsum content (mean = 6.9%) and abundant carbonates (mean CO₃⁼ = 40.7%). The predominant textures were silty loams with a high stone content (mean = 33.1%). SOC and SIC content ranged between 0.6 and 10.8% and between 0.8 and 8.6%, respectively.

The mean SOC content was significantly higher in uncultivated (4.0%) than in cultivated (1.5%) sites, and in concave (3.8%) than in convex (2.5%) sites, while slightly higher mean values were found in depositional than in erosional sites (Table 1). The mean SIC content was slightly higher but no significantly different in uncultivated and convex sites against cultivated and concave sites. For most properties no significant differences were found between erosional and depositional sites, apart from significantly higher mean content of sand and EC and lower mean content of clay in depositional than in erosional sites (Table 1).

Based on ¹³⁷Cs inventories the estimated soil redistribution rates for each soil profile (Fig. 2) the maximum thickness of soil gained and lost varied from from +3.59 to -4.40 mm ha⁻¹ yr⁻¹, respectively (Table 2). In both erosional and depositional sites, the thickness of soil lost or gained was significantly higher in the cultivated sites (mean = +1.5 and -1.8 mm ha⁻¹ yr⁻¹) than in the uncultivated ones (mean = +0.3 and -0.7 mm ha⁻¹ yr⁻¹). Regarding the curvature, even if differences were no significant, higher soil loss was

found in convex than in concave sites (mean = -1.4 against -0.4 mm ha⁻¹ yr⁻¹), and the contrary was observed for the soil gained, with higher soil thickness accumulated in concave than in convex sites, where it did not exceed +0.4 mm ha⁻¹ yr⁻¹. The water erosion-induced carbon loss and gain was also highly variable ranging between -0.8 and +1.4 Mg of SOC ha⁻¹ yr⁻¹ and between -5.9 and +1.3 Mg of SIC ha⁻¹ yr⁻¹ (Table 2) based on equation 1.

3.2. Flow accumulation and curvature effects on soil and carbon loss and gain

An intricate mosaic of land uses, different geomorphic elements, and topographic attributes along the slopes, result in a complex spatial pattern of the accumulative flow in the study catchment (Fig. 1). The modified stream order Strahler map results in the decrease of the slope lengths that were shortened and the consequent change in the upslope contributory areas. The flow accumulation map recorded low values for the 64% of the total surface catchment, while medium (28%) and high (8%) flows concentrated in the steepest areas where high accumulation of flowing water was observed. In Figure 3, the general trends from lowest to highest flow accumulation values, showed a significant increase in the loss of soil, SOC and SIC, respectively, though with weak correlation coefficients ($r = -0.354, -0.269, -0.387$, respectively).

An increasing trend in the gain of SOC and SIC (Mg ha⁻¹ yr⁻¹) was consistently associated with increasing soil gain (Fig. 4). A positive correlation was found between the thicknesses of soil gain with SOC ($r = 0.891$) and SIC ($r = 0.849$) Mg ha⁻¹ yr⁻¹, respectively. These correlations were similar and yet significant when topsoil samples were grouped by land use and curvature (Fig. 4 and Table 3). The stronger correlation for SOC was found for uncultivated samples in concave areas, while for SIC was for

uncultivated samples in convex areas. Rather poor results were obtained for the cultivated samples located in convex sites for both SOC and SIC (Table 3).

Along the five transects, the individual rates calculated for the soil thickness, SOC and SIC gain and loss varied largely (see Fig. 2), reflecting on one hand, the diversity of land uses and the topography relief of the sampling sites, and on the other hand the water flow pathways (see Table 4).

3.3. Redistribution of soil, SOC and SIC by using a perceptual model

The point values of gain and loss of soil, SOC and SIC estimated at each sampling point (Fig. 2) were extrapolated to segments of 1-m wide and a length that ranged from 20 to 70 m by using the perceptual model (Fig. 5), which provide a sediment and carbon budget for the overall transects in T1 and T2, and for different transect sections in case of T3, T4 and T5 due to the presence of LLE (Table 5, 6, 7 and Fig. 5).

For transect T1, a high net soil loss was recorded for its short length (Table 5), and in accordance with the very low soil deposition (99% SDR) a low total gain of SOC and SIC was recorded (Table 6 and 7, respectively). In contrast, T2 yielded a low net soil loss with a SDR of 63 % (Table 5, Fig. 5). Despite one third less total erosion occurred in T2 than in T1, the net SOC loss in T2 was greater than in T1 (Table 6), because uncultivated topsoil in T2 had higher SOC content than the cultivated topsoil in T1 (means: 5% against 1%). The net SIC loss in T2 was much lower than in T1, but consistent since SIC content in the samples was similar in both transects (means: 4.6% against 4%) and the net soil loss mobilized was almost four times less in T2 than in T1 (Table 5).

The abrupt change in the slope curvature in T3, T4 and T5 divided these transects in two parts, above and below the respective inflexions which stopped runoff breaking the connectivity of mobilized soil, SOC and SIC along the transect. The first part is defined

from the head of each transect to the maximum convexity point and is characterized by indirect contributions to the lake through lateral water pathways (Fig. 5). The direct contribution to the lake is restricted to the second part, which is limited from the convex point to the bottom slope. Transect T3 was characterized by stability, with low values of both gain and loss of soil in areas with natural vegetation of forest and old terraced fields located at the upper part (section 3a) as well as in the sections 3c and 3d, despite high soil gain and loss occurred in the cultivated areas at the mid slope prior the inflexion (section 3b), which resulted in null net loss of soil, SOC and SIC (Table 5, 6 and 7). In T4 soil loss predominated, reaching high values in steep cultivated sites, while soil gain was restricted to the terraces and in concave areas. *Las Lomas* hill braked the connectivity of T4 dividing the transect in two parts (Fig. 5). In the first section (4a) with uncultivated terraces, stability prevailed while the steep cultivated section (4b) recorded high total soil loss and also relative high soil gain restricted to the concave segment where sediments accumulated before the hill, recording 60% of SDR and a net loss of SOC and SIC of 2 and 16 kg yr⁻¹, respectively (Table 6 and 7). In the second part of T4 all segments experienced soil loss, obtaining 100% of SDR in the absence of deposition. The uncultivated section 4c produced small losses of soil and carbon, while in the cultivated sections 4d and 4e the net soil loss was much higher (Table 5) producing greater mobilization of SOC (Table 6) and SIC in section 4d, which coincided with a change of soil type (Table 7). Transect T5 recorded the maximum loss and gain of soil of all the five transects (Table 5) and a limestone Muschelkalk outcrop divided T5 in two parts. The first 570 m of uncultivated soils (sections 5a and 5b) experienced lower net soil loss than the 495 m below the outcrop where cultivated sites are located (Table 5); however, similar net SOC loss was obtained in parts 1 and 2, while higher net SIC loss was observed in part 1. The cultivated steep sections 5c and 5d (Fig. 5) were characterized by high net soil

losses with the maximum SDR and the highest net SOC and SIC exported in section 5d. The gentle cultivated areas at the bottom part of T5 (sections 5e and 5f) recorded high soil erosion but higher soil deposition, resulting in the absence of sediment and carbon delivery (Table 5, 6 and 7).

3.4. Sediment and carbon budgets

The sediment and carbon budgets established for each transect showed large variability (Tables 5 to 7, Fig. 5). The predominant soil redistribution processes, the topsoil carbon content, the curvature and the presence or absence of LLE along the transects, conditioned the mobilized soil, SOC and SIC susceptible to be deposited in the *Estanque Grande de Abajo* Lake (Fig. 6). In T1, the absence of LLE that could retain sediment resulted in a direct contribution of the soil and carbon mobilized. Along T2 the presence of depositional areas at mid and bottom slopes positions and a dirt road between points T2-6 and T2-7 would interrupt runoff for low intensity rainfalls and the contribution of soil, SOC and SIC to the lake would be restricted to the last 50 m section located after the road. In T3, the predominance of sedimentation is attributed to the presence of terraced slopes in the headland, dense vegetation strips in the form of ridges and changes in the geometry of the topographic profile that generate concave surfaces before the hill that retained the mobilized sediment. Therefore, in T3 the contributions to the *Estanque Grande de Abajo* Lake are practically non-existent (Fig. 6). The potential highest contribution of sediments and carbon to the lake were identified in T4 and T5 (Fig. 6). However, when considering LLE the sediment budgets showed that the net soil loss was reduced by up to 88% in T4 being also negligible the apports of the mobilized soil and carbon in T5.

4. Discussion

4.1. Control factors on soil, SOC and SIC redistribution

4.1.1. Flow accumulation and curvature effects

The numerous landscape linear elements in the catchment affect the overland flows mainly produced by topographic thresholds (slope inflexion, changes from gentle to steep slopes and vice versa), besides the presence of human infrastructures (terraces and trails) that influence runoff pathways from upslope to the lake. The velocity of flowing water becomes greater as slope gradient increases (Mu *et al.*, 2015), and a larger runoff velocity allows flowing water to detach and transport additional soil material. Consequently, an increased accumulation of runoff flow on steeper and longer slopes as in T5 results in greater rill erosion. However, the terraces located on the steep upper parts of T3 and T4 built perpendicular to the slope reduce erosion by decreasing overland flow length as well as the upslope contributory area, as also reported by Di Stefano *et al.* (2000) in a Mediterranean catchment in Italy. Hence, sediment settles as runoff travels at relatively low velocities along the gentle grades used in terraces. Our results showed that convex slopes with a larger gradient at the bottom slope are more erosive than concave surfaces, while deposition frequently occurs at the bottom and concave parts of slopes because of the reduced transport capacity of flow (T4-8). The shape of the slope determines that the highest depth of soil lowering is recorded at cultivated convex landform positions, while the decrease of the slope gradient at the bottom slope at the lowest position around the lake lead to deposition of the soil particles what is confirmed by high deposition thickness found at the base of T5. Therefore, in agreement with Hurst *et al.* (2012) that modelled the relationships between dimensionless erosion rate and hillslope curvature metrics we found that topographical parameters such as slope gradient and curvature have a strong effect on soil redistribution.

The positive relationships between flow accumulation and soil and carbon loss suggest that we were able to depict runoff and its effects on soil and carbon mobilization using a 5 m DEM. According to Lu et al. (2017), the resolution of a DEM should be as higher as possible to account for the impacts of rill and interrill water erosion on flow accumulation maps. Nevertheless, our consistent results are very useful for capturing the soil and carbon response along the studied transects and support that sediment availability and hydrological connectivity determine the hillslope sediment supply as it was also reported by Russell et al. (2019).

4.1.2. Land use and vegetation cover effects

Besides the influence of LLE and topographic relief, the high spatial variability of vegetation cover on steep slopes is associated with high variability of runoff at small scale due to generation of zones of preferential infiltration (Puigdefábregas et al., 1999; Schwannghart et al., 2011). At the upper part of T5 despite the length of the steepest section that would lead to increasing runoff (Figure 2) and subsequent increased erosion the dense vegetation cover counteracts such effect as the thickness of soil lowering here is moderate apart in one point. The physiography of the next section downslope after the rock outcrop combines both the increased flow accumulation (Fig. 2) with the mixed land uses that result in large variation of soil redistribution with both high thicknesses of soil loss and gain. The moderate values of soil loss and gain in uncultivated points (both did not exceed 1.6 mm yr^{-1} , even in steep areas) confirm the protective effect of the vegetation cover. Similar findings have been reported by Wang et al. (2010, 2019); Navas et al. (2014); Gaspar et al. (2019). However, the opposite occurs in cultivated steep sites where soil loss doubled the values of uncultivated sites because runoff is not constrained by the vegetation cover. Moreover, concave areas and flat cultivated sites at the bottom part of

the transects also recorded twice of maximum soil gain than in uncultivated sites. Therefore, vegetation has a significant effect on water erosion processes, intercepts rainfall and protects soil from raindrop impacts by reducing the energy of raindrop through raindrop size fragmentation. Besides, the flow velocity is reduced by absorbing some of the erosion energy (Beguería et al., 2015). Vegetation may also provides mechanical protection against overland flow detachment (Zhu et al. 2014). On the contrary the absence of natural vegetation cover and of LLE in the entirely cultivated T1 would restrict infiltration increasing runoff and its erosive power what results in increased thickness of soil loss downslope in agreement with high values of flow accumulation (Fig. 2). Our results confirm soil stability and accumulation of SOC at the upper part of the transects, characterized by stable gentle slopes at the divides that are densely vegetated. However, at mid-slope sections erosion processes lead to increase soil instability as also observed by Navas et al. (2014) and in other environments by Hurst et al. (2012) what decreased SOC. In the lower part of the transects under cultivated conditions and gentle slope, SOC content slightly increases which most likely favours geomorphic processes that transfer SOC from steep slope areas to gentle depositional areas via soil erosion.

We found that topography, which is a primary environmental parameter, affects SOC levels, but the variations due to land use differ from landforms as also found by Huang et al. (2015). Steep areas often experience soil erosion and are potential source of runoff and sediment (Chaplot et al., 2009) as we specially observed in transect T5, while the high SOC in the sediment from the topsoil of the upper part and steep areas is retained in depressions, as also recorded by Ritchie et al. (2007).

4.2. Lateral mobilization and sediment and carbon budgets

During normal rainfalls the LLE restrict runoff and the downslope transfer of mobilized soil, SOC and SIC. However, it appears that the concave cultivated areas located prior the hills which divided T3 and T4 into two parts and where sediments and carbon are stored can supply sediments to the lake if they are laterally connected to the drainage system. Nevertheless, during intense and erosive rainfall events only the hills and the thick limestone outcrop that creates a main inflexion of the slope curvature can interrupt the mobilization of soil and carbon along transects.

The key role that land use plays for SOC is supported by the comparable values of SOC net loss for cultivated moderate slope (T1) than for uncultivated slope (T2) despite having a soil net loss more than 10 times greater for the cultivated than for the uncultivated transect. The eroded sediment in T2 is relatively SOC enriched compared to the cultivated soils of T1. On the contrary, our results indicate a minor influence of land use for SIC. Several studies highlight the importance of the soil type on carbonate content particularly in karst areas (Gaspar et al., 2014) and the pedogenic processes on SIC redistribution (Yang et al., 2017). In agreement with Quijano et al. (2020), the highest content of soil inorganic carbon in cultivated downslope (e.g. T4) may be related with macro-aggregates along with little dispersed coarse sized particles that points to the existence of lithogenic or/and secondary carbonates as binding agents. Thus, the influence of the soil type affects the SIC content in this catchment where more than 80% of soils are carbonate rich soils.

A significant proportion of sediments and mobilized carbon supplied along the slopes is likely temporarily trapped along the hillslopes and not all the soil and carbon transported reaches directly the *Estanque Grande de Abajo* Lake. The extrapolation of transect appraisals to the overall catchment provides a SDR estimates of 59%. Therefore,

a bit more than 40% of sediments and mobilized carbon by erosion is deposited along the slopes before reaching the lake.

The mean SOC and SIC exported to the lake represents roughly half of the total SOC and SIC lost across the catchment. This implies that the net carbon loss in our catchment contributes to the carbon sinks in the *Estanque Grande de Abajo* Lake. Other studies also reported important sinks composed of carbon exported from catchments entering into the aquatic ecosystems (Yoo et al., 2006; Yue et al., 2016).

The marked differences between the gain and loss of soil and SOC in concave and convex areas that we have recorded in our study reveal how well-connected concave slopes with predominant interrill erosion deliver rich organic carbon sediment, as it was also reported by Boix-Fayos et al. (2017). Our results point to the significance of landform position on the erosion-induced terrestrial carbon sink and C sequestration, as reported by other authors (Rosenbloom et al., 2006; Berhe et al., 2008).

The interactions between topography and land use produce significant positive or negative effects on SOC and SIC accumulation, particularly in areas with complex topography, as the results obtained in our study sustain. Even though the effect of topography and land use/land cover and their interactions on the horizontal distributions of carbon remains largely unknown, our approach contributes to better understand the pattern of gains and losses of soil organic and inorganic carbon induced by water erosion.

5. Conclusions

From a geomorphological perspective, the integrated approach employed in this study provides a useful basis for estimating and improving our understanding of mobilization, transport and storage of soil and carbon in the landscape. Our attempt described the response and behaviour of soil and carbon displaced by water erosion along

the transects, giving a reasonable overview of topsoil mobilization within the catchment and subsequent exportation of soil and carbon to the lake.

The use of ^{137}Cs inventories along with the characterization of terrain attributes allowed us to identify whether erosional or depositional processes have been predominant in each study site. Our results provide sediment and carbon budgeting along the five transects using a perceptual model in combination with ^{137}Cs inventories, obtaining not only detailed information on individual segments and different sections of the delivery system along the transects but also gaining knowledge on the sediment and carbon budget.

Erosion and depositional processes play an important role in determining landscape scale topsoil SOC distribution, and it also indicates that SOC and sediments follow similar redistribution pathways. However, the erosion-induced topsoil SIC distribution is much less responsive, highlighting the key influence of the substratum origin and pedogenic processes. We can conclude that the presence of LLE creates hydrological disconnection reducing runoff and sediment supply. The budgets obtained allow us for the first time to have a quantitative estimation of the potential contribution of sediments, SOC and SIC to the *Estanque Grande de Abajo* Lake.

Despite the limitations of this approach, our findings provide information for understanding contemporary sediment and carbon surface mobilization by sheet and rill erosion in complex karst catchments, highlighting the important role of the landscape topography, the effect of runoff on different land uses and the importance of “intra-storage” of mobilized soil and carbon along the hillslopes.

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Figure 1. Location of the study site. Maps of a) the drainage network, including the stream order and landscape linear elements, and b) the reclassified flow accumulation for the catchment.

a) Stream order and landscape linear elements map

b) Flow accumulation map

645 **Figure 2.** Slope profiles and location of the 58 topsoil samples along the five transects.
 646 Variations of SOC and SIC contents (%), rates of soil thickness gained or lost (mm ha^{-1}
 647 yr^{-1}) based on calibration of ^{137}Cs inventories, and the estimated gain and loss of SOC
 648 and SIC ($\text{Mg ha}^{-1} \text{yr}^{-1}$) in each sampling site. *Positive values refer to gain and negative*
 649 *values refer to loss.*

Figure 3. Scatter plots of flow accumulation (log) versus gain and loss of a) SOC (Mg ha⁻¹ yr⁻¹), b) SIC (Mg ha⁻¹ yr⁻¹) and c) soil (mm ha⁻¹ yr⁻¹). Blue lines represent the fitted linear models, darker coloured stripes indicate the confidence bands, and the lighter coloured stripes the prediction bands. Dashed lines indicate the limits between values of gain (positive) and loss (negative) of each variable. P-value below 0.05 means a statistically significant relationship at the 95.0% confidence level.

Figure 4. Scatter plots of gain and loss of soil ($\text{mm ha}^{-1} \text{ yr}^{-1}$) versus the gain and loss of
a) SOC ($\text{Mg ha}^{-1} \text{ yr}^{-1}$) and b) SIC ($\text{Mg ha}^{-1} \text{ yr}^{-1}$). Lines represent the fitted linear models
when include: i) all samples, ii) cultivated samples at concave sites, iii) cultivated samples
at convex sites, iv) uncultivated samples at concave sites and v) uncultivated samples at
convex sites.

Figure 5. Estimates of loss and gain of soil, SOC and SIC (kg yr⁻¹) for individual 1-m wide segments along the transects.

Figure 6. Schematic sediment budgets obtained for the potential sections that contribute to the lake for each of the study transects.

Table 1. Summary statistic of the main topsoil properties at erosional and depositional sites. Asterisks indicate significant differences between erosional and depositional sites.

	Erosional sites n=28						Depositional sites n=30				
	Mean	SD	Median	Min	Max		Mean	SD	Median	Min	Max
SOC %	2.98	±2.78	1.94	0.62	10.81		3.27	±1.83	3.21	0.84	7.51
SIC %	4.91	±1.80	4.61	1.78	8.50		4.87	±2.11	4.65	0.81	8.56
Stoniness %	33.53	±16.71	33.86	2.40	80.11		32.68	±19.43	29.75	2.73	76.18
pH H ₂ O	8.26	±0.26	8.35	7.68	8.59		8.24	±0.16	8.27	7.87	8.60
EC %	0.32	±0.40	0.22	0.14	2.29	*	0.42	±0.55	0.25	0.15	2.45
CO ₃ ⁼ %	40.89	±14.98	38.35	14.87	70.86		40.55	±17.56	38.70	6.74	71.31
Gypsum %	6.25	±3.46	5.17	2.57	14.95		7.52	±3.94	6.86	2.20	20.17
Sand %	5.63	±6.76	4.15	0.00	29.37	*	13.65	±19.39	7.80	0.00	76.34
Silt %	71.89	±5.09	73.12	51.58	77.64		67.26	±14.73	72.07	17.31	84.94
Clay %	22.48	±3.45	22.00	15.90	30.34	*	19.09	±7.08	19.95	4.30	34.59

* 95% confidence level (P-value < 0.05)

* 90% confident level (P-values < 0.1)

Table 2. Summary statistics of gain (positive values) and loss (negative values) of soil thickness (mm ha⁻¹ yr⁻¹), SOC and SIC (Mg ha⁻¹ yr⁻¹) at the sampling sites.

		Erosional sites n=28					Depositional sites n=30				
		Mean	SD	Median	Min	Max	Mean	SD	Median	Min	Max
Soil	mm ha ⁻¹ yr ⁻¹	-1.25	±1.14	-1.04	-0.01	-4.40	0.53	±0.82	0.16	0.01	3.59
SOC	Mg ha ⁻¹ yr ⁻¹	-0.26	±0.19	-0.22	-0.00	-0.78	0.15	±0.26	0.05	0.00	1.36
SIC	Mg ha ⁻¹ yr ⁻¹	-0.89	±1.34	-0.49	-0.00	-5.89	0.27	±0.39	0.07	0.00	1.35

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Table 3. Pearson correlation coefficients between gain and loss of soil ($\text{mm ha}^{-1} \text{yr}^{-1}$) and gain and loss of SOC and SIC ($\text{Mg ha}^{-1} \text{yr}^{-1}$), respectively, for the topsoil samples grouped by the land use (cultivated and uncultivated) and the curvature of the sampling site (concave and convex).

	n	SOC $\text{Mg ha}^{-1} \text{yr}^{-1}$	SIC $\text{Mg ha}^{-1} \text{yr}^{-1}$
Soil $\text{mm ha}^{-1} \text{yr}^{-1}$	58	0.891 *	0.849 *
<i>Cultivated - Concave</i>	6	0.921 *	0.949 *
<i>Cultivated - Convex</i>	14	0.569 *	0.679 *
<i>Uncultivated - Concave</i>	21	0.941 *	0.891 *
<i>Uncultivated - Convex</i>	17	0.921 *	0.989 *

Table 4. Kruskal-Wallis test for gain and loss of soil, SOC and SIC by a) land use and b) curvature. Asterisks indicate significant differences between uncultivated and cultivated sites, and concave and convex sites, respectively.

		Land use			Curvature		
		Uncultivated	Cultivated		Concave	Convex	
<i>Erosional sites</i>							
Soil	mm ha ⁻¹ yr ⁻¹						
1		0.38	1.67	*	0.32	1.15	*
SOC	Mg ha ⁻¹ yr ⁻¹						
1		0.12	0.24	*	0.19	0.22	
SIC	Mg ha ⁻¹ yr ⁻¹						
1		0.13	0.76	*	0.10	0.61	*
<i>Depositional sites</i>							
Soil	mm ha ⁻¹ yr ⁻¹						
1		0.09	1.46	*	0.19	0.16	
SOC	Mg ha ⁻¹ yr ⁻¹						
1		0.03	0.28	*	0.05	0.05	
SIC	Mg ha ⁻¹ yr ⁻¹						
1		0.05	0.73	*	0.05	0.11	

* 95% confidence level (P-value < 0.05)

* 90% confident level (P-values < 0.1)

Table 5. Sediment budget for each section along the five transects. Grey numbers indicate indirect contributions to the lake.

Soil	Length m	Total loss kg yr ⁻¹	Total gain kg yr ⁻¹	Net loss kg yr ⁻¹	SDR %	Segment net loss Mg ha ⁻¹ yr ⁻¹
T1 <i>Section 1a</i>	175	230.00	2.25	227.75	99.0	13.01
T2 <i>Section 2a</i>	275	75.75	27.50	48.25	63.7	1.76
<i>Section 2b</i>	50	0.00	0.50	-	-	-
T3 <i>Section 3a</i>	215	22.25	44.92	-	-	-
<i>Section 3b</i>	190	180.05	261.60	-	-	-
<i>Section 3c</i>	70	0.00	15.00	-	-	-
<i>Section 3d</i>	100	0.50	6.00	-	-	-
T4 <i>Section 4a</i>	110	0.00	53.66	-	-	-
<i>Section 4b</i>	265	440.50	184.42	156.08	58.1	96.63
<i>Section 4c</i>	95	15.50	0.00	15.50	100.0	16.37
<i>Section 4d</i>	105	475.20	0.00	475.20	100.0	45.26
<i>Section 4e</i>	50	76.50	0.00	76.50	100.0	15.30
T5 <i>Section 5a</i>	425	112.00	56.78	55.23	49.3	1.30
<i>Section 5b</i>	145	65.70	5.62	60.09	91.5	4.14
<i>Section 5c</i>	45	65.95	0.00	67.95	100.0	15.10
<i>Section 5d</i>	265	650.86	129.93	520.93	80.0	19.66
<i>Section 5e</i>	85	0.00	121.25	-	-	-
<i>Section 5f</i>	100	86.00	86.50	-	-	-

712 **Table 6.** SOC budget for each section along the five transects. Grey numbers indicate
 713 indirect contributions to the lake.

714

SOC	Length m	Total loss kg yr ⁻¹	Total gain kg yr ⁻¹	Net loss kg yr ⁻¹	SDR %	Segment net loss Mg ha ⁻¹ yr ⁻¹
T1 <i>Section 1a</i>	175	2.59	0.02	2.57	99.3	0.15
T2 <i>Section 2a</i>	275	3.66	0.87	2.80	76.4	0.10
<i>Section 2b</i>	50	0.00	0.03	-	-	-
T3 <i>Section 3a</i>	215	0.74	0.70	-	-	-
<i>Section 3b</i>	190	2.56	9.90	-	-	-
<i>Section 3c</i>	70	0.00	0.5	-	-	-
<i>Section 3d</i>	100	0.02	0.15	-	-	-
T4 <i>Section 4a</i>	110	0.00	1.15	-	-	-
<i>Section 4b</i>	265	4.28	2.23	2.06	48.0	0.08
<i>Section 4c</i>	95	1.32	0.00	1.32	100.0	0.14
<i>Section 4d</i>	105	3.46	0.00	3.46	100.0	0.33
<i>Section 4e</i>	50	3.01	0.00	3.01	100.0	0.60
T5 <i>Section 5a</i>	425	4.02	2.14	1.88	46.8	0.04
<i>Section 5b</i>	145	2.29	0.29	2.00	87.3	0.14
<i>Section 5c</i>	45	0.99	0.00	0.99	100.0	0.22
<i>Section 5d</i>	265	7.54	4.02	3.52	46.7	0.13
<i>Section 5e</i>	85	0.00	1.53	-	-	-
<i>Section 5f</i>	100	0.93	1.10	-	-	-

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717 **Table 7.** SIC budget for each section along the five transects. Grey numbers indicate
 718 indirect contributions to the lake.

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SIC		Length m	Total loss kg yr ⁻¹	Total gain kg yr ⁻¹	Net loss kg yr ⁻¹	SDR %	Segment net loss Mg ha ⁻¹ yr ⁻¹
T1	<i>Section 1a</i>	175	8.62	0.10	8.52	98.8	0.49
T2	<i>Section 2a</i>	275	3.41	0.61	2.79	82.0	0.10
	<i>Section 2b</i>	50	0.00	0.03	-	-	-
T3	<i>Section 3a</i>	215	1.20	3.17	-	-	-
	<i>Section 3b</i>	190	6.00	9.60	-	-	-
	<i>Section 3c</i>	70	0.00	0.66	-	-	-
	<i>Section 3d</i>	100	0.02	0.51	-	-	-
T4	<i>Section 4a</i>	110	0.00	2.88	-	-	-
	<i>Section 4b</i>	265	22.19	6.08	16.11	72.6	0.61
	<i>Section 4c</i>	95	0.68	0.00	0.68	100.0	0.07
	<i>Section 4d</i>	105	37.31	0.00	37.31	100.0	3.55
	<i>Section 4e</i>	50	2.44	0.00	2.44	100.0	1.62
T5	<i>Section 5a</i>	425	8.33	3.35	4.98	59.8	0.12
	<i>Section 5b</i>	145	3.35	0.39	2.97	88.49	0.20
	<i>Section 5c</i>	45	3.50	0.00	3.50	100.0	0.78
	<i>Section 5d</i>	265	35.07	4.82	30.35	86.3	1.14
	<i>Section 5e</i>	85	0.00	5.59	-	-	-
	<i>Section 5f</i>	100	2.19	1.80	-	-	-

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