Carbon redistribution by erosion processes in an intensively disturbed catchment

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Abstract

Understanding how organic carbon (OC) moves with sediments along the fluvial system is crucial to determining catchment scale carbon budgets and helps the proper management of fragile ecosystems. Especially challenging is the analysis of OC dynamics during fluvial transport in heterogeneous, fragile, and disturbed environments with ephemeral and intense hydrological pulses, typical of Mediterranean conditions. This paper explores the catchment scale OC redistribution by lateral flows in extreme Mediterranean environmental conditions, from a geomorphological perspective. The study area is a catchment (Cárcavo) in SE Spain with a semiarid climate, erodible lithologies, and shallow soils, which is highly disturbed by agricultural terraces, land levelling, reforestation, and construction of check-dams. To increase our understanding of catchment scale OC redistribution induced by erosion, we studied in detail the subcatchments of eight check-dams distributed along the catchments main channel. We determined ^{137}Cs, physicochemical characteristics, and the OC pools of the catchment soils and sediments deposited behind each check-dam, performed spatial analysis of catchment properties and buffer areas around the check-dams, and carried out geomorphological analysis of the slope-channel connections.

The soils showed very low total organic carbon (TOC) values, oscillating between 15.2 and 4.4 g kg^{-1} for forest and agricultural soils, respectively. Sediments mobilized by erosion were poor in TOC compared to the eroded (forest) soils (6.6±0.7 g kg^{-1}), and the redistribution of OC through the catchment, especially of the mineral associated organic carbon (MAC) pool, showed the same pattern as clay particles and ^{137}Cs. The TOC erosion rates estimated for the Cárcavo watershed are relatively low (0.031±0.03 Mg ha^{-1} y^{-1}) but similar to those reported for subhumid Mediterranean catchments that are less fragile and more conducive to plant growth. The TOC erosion/total erosion ratio was lower (0.06 %) than other estimates, although the average OC concentration of the sediments was higher than that of the agricultural soils of the catchment, underlining the problem of maintaining sustainable soil OC contents.

The OC in deposited sediments came not only from surface erosion processes, but also from deeper soil or sediment layers mobilized by concentrated erosion processes. Sediment richer in OC came from the surface soil of vegetated (reforested) areas close and well connected to the channels. Subcatchments dominated by laminar erosion processes showed a TOC erosion/total erosion ratio that was two times higher than that of subcatchments dominated by concentrated flow erosion processes. The lithology, soils, and geomorphology exert a more important control on OC redistribution than land use and vegetation cover in this geomorphologically very active catchment.

1. Introduction

Recently, fluvial sediments have been identified as important organic carbon (OC) sinks with potentially strong implications for catchment and regional carbon (C) budgets (Hoffman et al., 2013; Ran et al., 2014; Boix-Fayos et al., 2015). However, the fluvial and geomorphological conditions and dynamics determine the quality and quantity of OC mobilized by sediments (Hoffman et al., 2013), as well as the post-depositional processes that might affect OC fluxes and in turn the OC sink (Van Hemelryck et al., 2011; Berhe and Kleber, 2013). In semiarid and arid environments with episodic and intense hydrological events, alternating with small events and long drought periods, the OC redistribution due to lateral flows is complex and is not well defined. Better knowledge of the processes involved in the OC redistribution in semiarid, fragile environments would help their management, to at least maintain ecologically sustainable levels of OC in soils and sediments. This work explores the OC pools mobilized by lateral flows in a fragile, semiarid environment and tries to add to our knowledge of these processes.

Lateral flows of sediment are affected by agricultural management practices (Van Oost et al., 2007; Martinez-Mena et al., 2008; Quijano et al., 2016), which influence runoff production, soil stability, sediment detachment, and available soil organic carbon (SOC) in the soil surface - and thus the SOC detached and transported at the slope scale (Martínez-Mena et al., 2012; Nadeu et al., 2015b; Quijano et al., 2016). Multiple experiments at the plot and field scales showed selective erosion of fine particles and enrichment of SOC in sediments, compared to the original soils (Avnimelech and McHenry, 1984; Starr et al., 2000; Jin et al., 2009; Martínez-Mena et al., 2012). However, the redistribution of OC by lateral flows at the watershed scale seems to be much more complex due to the interference of other ecogeomorphological processes (Boix-Fayos et al., 2015). Organic C redistribution through the fluvial system is affected not only by agricultural management but also by land use (Boix-Fayos et al., 2009), that partially determines the channel-slope connectivity by different erosion processes (Nadeu et al., 2011 and 2012).

Furthermore, past studies have demonstrated the links between SOC yields in watersheds and the morphological properties of the drainage area, as well as relationships between land use and vegetation cover and the concentration of OC in sediments (Boix-Fayos et al., 2009; Nadeu et al., 2015a). Also, the dominant erosion processes in a catchment influence the concentration and quality of the OC present in the eroded sediments (Nadeu et al., 2011).

Therefore, to determine C budgets at the catchment scale, it is crucial to understand how OC moves with sediments along fluvial paths (Hoffmann et al., 2013). In particular, little is known of how OC is redistributed in fragile environments with a variety of lithologies, land uses, and ephemeral hydrological and sedimentological pulses, typical of Mediterranean conditions. The aim of this work was to characterize and analyze the OC redistribution by lateral flows in a Mediterranean catchment with erodible lithologies and shallow soils, and which is highly disturbed by agricultural terraces, land levelling for agriculture, reforestation, and construction of check-dams. The specific objectives were to: i) quantify the total OC mobilized by erosion at the catchment scale, ii) link the C redistribution to sediment properties and morphological characteristics of the drainage areas and channels, and iii) determine the factors controlling the quality and quantity of the mobilized OC.

We hypothesize that the abiotic characteristics of catchments (lithology, topography, geomorphology) impose a template for C redistribution by lateral flows. This template is more dominant than biological and ecological factors with regard to C redistribution by lateral processes in semiarid and fragile ecosystems.

2. Study area

The study was performed in the Cárcavo catchment, located in SE Spain, in the Region of Murcia (38°13′ N; 1°31′ W). It is a catchment of 2732 ha with a semiarid climate, an average annual precipitation of 279 mm, an average annual evapotranspiration of 848 mm (data from the nearby Alfonso XIII reservoir), and high intensity rainstorms. In the catchment, marls, limestones, and Quaternary deposits appear. The catchment is surrounded by limestone and dolomite ridges, with outcrops of Keupers clays, and the basin is filled with Miocene marls. The lithology is highly erodible and abundant erosive morphologies appear. Since the 1970s the area has been highly disturbed by hydrological control works consisting of terracing, several phases of reforestation, and the construction of 36 check-dams for flood control and sediment retention. Large areas were used for extensive agriculture (cereals, almonds), first in terraces (many abandoned nowadays) and later in levelled terrains.

Eight subcatchments, delimited by check-dams and located in the main channel, were selected to carry out this study (Figure 1). Table 1 shows some of their characteristics. The size of the subcatchments varied between 91 and 526 ha and the average slope of the catchments increased in a downstream direction (with the exception of the subcatchment of check-dam 31), being between 12 and 37 %. The dominant lithologies of the subcatchment areas were marls (48.5±14.5 %) and the most abundant soils were Regosols (66.5±26 %). The soils had an average pH of 8.5±0.0 and a $CaCO_3$ content of 48.6±3.03 %. The texture of the soils was silty clay loam.

3. Methods

The research methodology combined fieldwork (sampling of sediments at the subcatchment level, sampling of soils, and geomorphological mapping), laboratory analysis (physicochemical characteristics of sediments and soils), and spatial GIS analysis of subcatchment areas to extract subcatchment topographic properties.

3.1. Experimental design

Eight check-dams on the main stream - built between 1970 and 1980 - were selected for this study and their sediment wedges were sampled. For each one, nine undisturbed samples (0-30 cm) were collected with an auger. For each sediment wedge, three transects perpendicular to the channel were set up, on the apex, center, and close to the check-dam; in each transect three replicate samples were taken, on the extremes of the transect and in its center (in total, 72 samples).

Furthermore, a sedimentary profile of the subcatchment of check-dam 20 was sampled (Figure 1). This check-dam 20 collapsed in a flood and its alluvial wedge was almost completely eroded. The profile was taken in one of the lateral banks and was sampled to a depth of 325 cm (16 samples). The volume of the sediments forming the alluvial wedge retained behind each check-dam and the bulk density to convert it into mass units was taken from the previous work by Castillo et al. (2007). The mass of sediment trapped at each check-dam was divided by the drainage area of each subcatchment and by the years since check-dam construction to obtain the specific sediment yield (SSY, Mg ha^{-1} y^{-1}), after correction by the specific trap efficiency of each check-dam according to Boix-Fayos et al. (2008). The specific carbon yield or total organic carbon (TOC) erosion rate (Mg ha^{-1} y^{-1}) was estimated by combining the average C concentration of the sediment samples in the central transect of the sediment wedge and the specific sediment yield (Boix-Fayos et al., 2009). The particulate organic carbon (POC) erosion rate and mineral associated organic carbon (MAC) (Mg ha^{-1} y^{-1}) erosion rate were estimated in the same way but using, respectively, the POC (g kg^{-1}) concentration and MAC concentration (g kg^{-1}) of the alluvial wedge at each subcatchment.

Furthermore, entire soil profiles were sampled in several subcatchment areas on agricultural (3 profiles) and forested land (3 profiles).

All samples were analyzed in the laboratory for physical and chemical properties (93 samples). A subset of samples was analyzed for ^{137}Cs (44 samples) and OC (26 samples).

3.2. Laboratory analysis

All soil and sediment samples were air-dried or dried in an oven at a low temperature (<60º) and then sieved at 2 mm. The pH and carbonate contents were analyzed according to standard procedures (CSIC, Consejo Superior de Investigaciones Científicas, 1976). The contents of the clay, silt, and sand fractions were measured by laser diffraction using a Coulter LS200. The samples were heated at 80^{o}C with 10 % H_20_2 to eliminate the organic matter, chemically disaggregated with hexametaphosphate (40 %), and stirred for 8 h; ultrasound was used to facilitate particle dispersion.

The OC was divided into physical fractions by wet sieving: the POC (>53 µm) was separated from the MAC (<53 µm) after shaking 10 g of air-dried soil, sieved at 2 mm, with 50 ml of sodium hexametaphosphate for 18 h (Cambardella and Elliot, 1992). The fractions were oven-dried at 60ºC, for water evaporation, and the dry material was weighed prior to OC determination. The OC and nitrogen contents were determined by dry combustion in an elemental analyzer (FLASH EA 1112 Series Thermo). The TOC was assumed to be the sum of the POC and MAC. Duplicate or triplicate soil samples were used for laboratory analysis.

For the ^{137}Cs analyses, soil samples were stored at 4ºC until their analysis in the laboratory. The samples were air-dried, ground, homogenized, and quartered, before being passed through a 2-mm sieve. The coarse and fine-earth fractions were separated and weighed to account for the content of stones (> 2 mm) and the total percentage of the < 2 mm fraction that fixes the ^{137}Cs radionuclide in the effective volume of the soil (Soto and Navas, 2004). Radionuclide activity in the soil samples was measured at the gamma laboratory of the EEAD-CSIC, using a high resolution, low background, low energy, hyperpure germanium, coaxial gamma-ray detector coupled to an amplifier and multichannel analyzer (Canberra Xtra, Canberra Industries Inc., USA). The methods used in the gamma analysis are described in detail in Navas et al. (2014). The detector is shielded to reduce the background and has an efficiency of 30% and 1.9 keV resolution at 1.33 MeV (60Co). The ^{137}Cs activity was determined from the 661.6 keV photopeak. The counting time was 30000 s and the analytical precision of the measurements was approximately ± 5% (95% level of confidence). The content of ^{137}Cs in the soil samples is expressed as a concentration or massic activity (Bq kg^{-1} dry soil).

3.3. Nested geomorphological analysis

Topographical and geomorphological variables were studied (i) at the subcatchment level, (ii) in buffer areas around the alluvial wedges, and (iii) in the slope-channel connections in fluvial reaches upstream of the alluvial wedges. The purpose was to achieve a better understanding of the influence of catchment areas and types of erosion processes on the lateral movement of OC.

3.3.1. Catchment, subcatchment scale, and buffer areas

The topography and catchment hydrological properties were calculated from a digital elevation model (DEM) obtained from airborne LiDAR data with a spatial resolution of 4 m (www.murcianatural.carm.es/natmur08/). The morphological variables derived from the DEM were slope (Slp), total curvature (Cu), profile curvature (CuP), planar curvature (CuPP) (Wilson and Gallant, 2000), and compound topographic index (CTI) (Oueslati et al., 2013).

The subcatchment areas of the check-dams and buffer areas of 100 m around drainage lines were extracted from the DEM.

Ortophotoimages from 1956, 1981, and 1997 (iderm.es) were used as a basis to digitize land use and land cover (LULC). The 1981 image captured the LULC during the period of check-dam construction and afforestation. Eight LULC classes were defined: high density forest (HDF), medium density forest (MDF), low density forest (LDF), reforestation (refi), shrubland (Shr), gullies (gul), agricultural fruit tree plantations (walnut and almonds) as well as irrigated vineyards (agrit), and rainfed cereal crops (agric).

The soil data, with the spatial distribution of taxonomic units classified according to the FAO System (1974), were obtained from the LUCDEME project (Scale 1:100,000) (ICONA, 1986). Lithological information was extracted from the National Geological Map (1:50,000) (MAGNA) (IGME, info.igme.es/cartografiadigital).

3.3.2. Channel morphological analysis

Morphological mapping of the channel reach, to approximately 75 m upstream of each check-dam, was carried out in the field. The morphological cartography described the slope-channel connections and the morphological features in the channel (Hooke, 2003; Boix-Fayos et al., 2007; Nadeu et al., 2011; Nadeu et al., 2012). This field morphological cartography reinterpreted the methods described by Hooke (2003), allowing the identification of: inputs of sediment to the channel system, zones of storage, signs of sediment transfer, and the net functioning of the channel reach. The cartography represented the main processes connecting the slopes and channel (interrill erosion processes, rills, gullies, bank erosion, creeping), the form of the slopes adjacent to the channel (convex, concave, cliff-talus), the lithology, land use, cover, and anthropic signs of the slopes (terracing, reforestation works, and constructions), and mapped the morphological features, erosional and depositional areas in the channel. All this together gave information on the sources and sinks of sediments and the transversal (slope-channel) and longitudinal (along the channel) connectivity of sediments.

3.4. Organic carbon mobilization by soil erosion

At the subcatchment scale, the estimation of the eroded C was based on the estimated volume of sediments retained by the check-dam at the outlet of each subcatchment, corrected by the trap efficiency, according to Brown (1943), to obtain the actual sediment yield. The eroded C (Mg C ha^{-1} $year^{-1}$) was calculated as the product of the mass of eroded sediment (kg) and the C concentration (g kg^{-1}) measured in the sediment, related to the drainage area and the year of check-dam construction (Boix-Fayos et al., 2009).

3.5. Statistical analysis

Differences in texture and TOC were tested using Generalized Randomized Complete Blocks (GRCB) ANOVA. The random factor (blocks) was the check-dams and the fixed factor was the sampling position within the sediment wedge (apex, center, close to check-dams). Variations in ^{137}Cs were tested by RCB: the random factor was the check-dam and the fixed factor was the position of the wedge along the upstream-downstream gradient.

The POC and MAC pools were measured only in a subset of samples (the central position of each check-dam); therefore, differences between check-dams were tested by ANOVA with only one random factor (check-dam).

In order to better understand the relationships between the basic attributes of the sediments (texture, POC, MAC, ^{137}Cs), Principal Component Analysis (PCA) was carried out. For the three analyses we performed also a Variance Components analysis in order to discern the proportion of the variance that could be allocated to each factor. All these analyses were carried out in the framework of general linear mixed models (GLMM), with the MIXED procedure of SAS 9.3.

To identify the environmental factors of the catchment areas that were associated with sediment characteristics, we worked at three scales: (i) check-dam subcatchment; (ii) 100-m buffer area around the perimeter of the sediment wedge; (iii) 75-m channel reach. For the two first scales the variables were extracted as explained in section 3.3.1. The morphological maps of the channel reaches (section 2.3.3) were quantified by assigning a "2" to a geomorphological feature if it was present on both banks of the channel, a “1” if it was present only on one bank, and a “0” if it was not present.

To balance the limited number of cases (8 subcatchments of check-dams) with the large number of environmental variables (>30), some tests to reduce the number of variables were carried out. The variables estimated for the subcatchments and buffer areas were grouped according to themes (topographical, lithological, and soil variables; 6 groups); in addition, there was another group related to the geomorphology of the channel. First, PCAs were applied to these groups and the first components extracted; second, analysis of the correlation between the first components of the PCA by groups was performed to reduce again the number of variables. Third, the components for which better correlations were obtained were chosen to be used as predictors in regression models. Regression models to explore the TOC and the organic pools (POC and MAC) were selected by forward stepwise regression, using the Akaike Information Criterion.

4. Results

4.1. Geochemical properties and organic carbon pools of sediments and soils

The soils of the catchment had very low TOC values: between 15.2 and 4.4 g kg^{-1} for forest and agricultural soils, respectively. The TOC concentrations in the alluvial wedges were higher, in general, in the upper and middle parts of the catchment (6-10 g kg^{-1}) than in the lower part (Table 1), where the TOC concentrations were similar to those in the agricultural soils (4 g kg^{-1}).

The concentration of OC associated with the mineral fraction (MAC pool) was higher in the middle part than in the upper or lower parts of the catchment, the contribution of this fraction to the total C being highest at check-dam 10 - where 88% of the TOC was present as MAC (Table 1, Figure 1). Regarding the particles deposited at the check-dams, a predominance of silt (on average, 60% of the total) followed by clay (30%) was observed, while sand particles were less mobilized to the deposits (an average of 11%). In general, the sediments in the middle part of the catchment had a higher proportion of finer material than those from the upper or lower part (Table 1). The concentration of ^{137}Cs increased from the upper part of the catchment to the middle part. The highest value was observed at check-dam 10 (1.97 Bq kg^{-1}), while no signal was observed in the lower part of the catchment.

The TOC differed significantly among the check-dams (Table 2; P=0.039, N=63). The interaction between the position in the wedge and the check-dam was also significant (P = 0.002), indicating that there were patterns of deposition within a wedge but that they were singular to each check-dam; that is, there was no common pattern of TOC deposition in the upstream-downstream gradient of the sediment wedges. The clay also varied significantly among check-dams (P<0.001) and the sand marginally so (P=0.068), but not within the wedges. Silt variation was significant (P=0.014) for the interaction of the check-dam with the position in the wedge. So, the sedimentation dynamics seem to be idiosyncratic to each check-dam/subcatchment.

The MAC content of the sediments differed significantly among the check-dams (P=0.031, ANOVA test). The proportion of the variance explained by the check-dam location was 50% (Variance Components Model). The TOC also differed marginally among the check-dams

(P=0.051, N=21), the variance explained by the check-dam location was 38 %. With respect to the ^{137}Cs, the effect of the check-dam was significant (RCB ANOVA, P=0.002) and explained 70 % of the variance; however, the effect of the position within the check-dam was not (P=0.359).

4.2. Sediment carbon yield and the relationship with sediment properties.

The average sediment yield in the catchment was about 6 Mg ha^{-1} $year^{-1}$, ranging between 0.85 at D9 and 23 Mg ha^{-1} $year^{-1}$ at D7 in the lowest portion of the catchment, although there was no well-defined pattern along the course of the catchment. A higher sediment yield led, in general, to greater total OC in the sediments (Table 3). The sediment C yield averaged 0.031 Mg ha^{-1} $year^{-1}$, about 0.6 % of the sediment yield. On average, about 70% of the TOC accumulated was in the MAC pool. The contribution of the MAC pool to the total sediment C was highest in the sediment wedges D10 and D8. When comparing the total OC with the total mobilized sediment (the TOC/total erosion ratio), the values observed in the middle part (D9 and D10) were higher than in the lower portion of the catchment.

Principal component analysis was conducted to explore the associations between the organic carbon pools and other sediment characteristics. Accounting for 81 % of the variance, the first component separated sediment wedges rich in clay, MAC, and ^{137}Cs from those rich in sand. The second component separated the sediment wedges with high POC and silt contents from those with high sediment C yield and rich in clay. The biplot clearly shows three groups of check-dams: 10 is isolated from the rest, 7 and 8 are very similar, and 9, 14, 16, and 31 form a gradient along the first PCA axis (Figure 3).

4.3. Land use changes and morphology of subcatchments and channels.

The land use changes were not very great in the period studied (1956-1997), agricultural land comprising around 40 % on the three dates studied (1956-1981-1997). The main change was the decrease in the badlands or gully areas from 1956 (13%) to 1997 (6%). The introduction of large reforestation areas (41% in 1981) (Figure 3) was also an important change in many subcatchments. The reforestation was performed mainly on pasture land (38 %), on shrubland (21 %), and in gullies (16%). Subcatchments 7 and 8 experienced the largest losses of agricultural land and, together with 9 and 31, experienced reforestation of more than 50 % of their catchment area in former agricultural, pasture, shrubland, and gully areas (Figure 4).

With respect to the geomorphological cartography, as described in the methods a channel reach upstream of each check-dam was mapped in the field to determine the dominant morphologies in the channel and in the slope-channel connections. The objective was to characterize the dominant erosion processes and the sources of the sediments transported to the channel (Figure 5 and 6). These data show that there were two opposite, extreme cases (types A and B) and another, transition group (type C): (i) type A: the channel reach belonging to check-dam 20, located downstream of the Cárcavo watershed, showed morphologies associated with the presence of bank erosion processes and large gullies with an armored, degraded channel. In contrast (ii) type B: the channel reach upstream of check-dam 10 was surrounded by reforested, concave slopes well connected to the channel with signs of interrill erosion processes and small superficial mass movements (creep morphologies). (iii) type C: the rest of the channel reaches described showed mixed situations, probably related to the characteristics of the immediate drainage areas (lithology, land use, and slope morphology) (Figure 6).

4.4. Factors controlling organic carbon export at the subcatchment level

The results of the PCA of the sediment characteristics at the outlet of the subcatchments (Figure 3) and the geomorphological analysis of the channels and slope-channel connections (Figures 5 and 6) show some parallelisms. Three main groups were obtained (Figure 3). These groups exhibited some correspondence with the different channel morphologies and dominant erosion processes observed in the field. At the two extremes appear: (i) check-dams 7, 8, and 20 (the latter does not appear in the PCA because the sediment yield could not be estimated for its catchment area) (type A) (Figures 3, 5, and 6) - which showed pronounced bank erosion processes and channel erosion, with areas adjacent to the channel providing sediments with low TOC and ^{137}Cs values. Check-dams 7 and 8 were already in transition to the next category but still exhibited concentrated and deep erosion processes (gullies, bank erosion) connected to the channel; and (ii) Check-dam 10 (and the relatively close check-dam 9), which represents type B. Check-dam 10 showed reforested slo pes, well connected to the channel through interrill erosion processes, and the highest TOC concentrations and ^{137}Cs values. (iii) In between the two former groups, the third group (type C) was comprised of wedges and channel reaches with a mixture of characteristics (check-dams 14, 16, and 31). These included both concave and convex slopes with gullies of different sizes and types, ephemeral gullies from agricultural slopes (with small debris cones or fan accumulations in the channel-slope connections) coming from dryland agricultural areas well connected to the channel through concave slopes, and (semi) natural slopes with convex connections to the channel (Figures 3, 5, and 6). These are located in the upper stream of the Cárcavo basin, on marl lithology areas with a mixture of natural and reforested vegetation and dryland agricultural areas. All showed aggradated channels.

The TOC was controlled by the combination of the four variables selected, the most significant being the lithology and soils of the buffer area. The POC pool was not satisfactorily explained by the input variables; the lithology and soils of the buffer area explained only 16 % of the variance of this pool. Regarding the MAC pool, 32% of its variance was explained by the lithology and soils of the buffer area (Table 6).

5. Discussion

5.1. Organic carbon mobilized by erosion at the catchment scale

The TOC concentrations in the sediments of the Cárcavo basin (6.6±0.7 gkg^{-1}) were, in general, much lower than those of the forest soils of the catchment (15.2±7.2 gkg^{-1}) and were closer to the average OC concentration of the very degraded agricultural soils (4.4±0.9 gkg^{-1}). Thus, the sediments circulating in the Cárcavo fluvial system are on average impoverished in OC, when compared to the values reported for eroded sediments obtained at smaller scales in erosion plots (Owens et al., 2002; 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 slope scale, sediments impoverished in TOC are found occasionally, when compared to reference sites (Quijano et al., 2016), but sediments enriched in TOC are found also due to high burial efficiency (Wang et al., 2015). At the catchment scale, both sediments impoverished in OC with respect to catchment soils (Haregeweyn et al., 2008; Boix-Fayos et al., 2009; Boix-Fayos et al., 2015; Chaplot and Poesen, 2012; Ran et al., 2014) and sediments enriched in TOC associated with the suspended load (Rhoton et al., 2006; Wang et al., 2010) 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., 2011; Nadeu et al., 2012; Boix-Fayos et al., 2015).

In the Cárcavo basin the OC was mainly associated with ^{137}Cs distribution and with fine mineral particles (Figure 3); thus, the mobilization of OC pools follows the same paths as fine sediments and ^{137}Cs at this watershed scale, as found by other authors at finer scales (particularly the slope scale) (Ritchie and McCarty, 2003; Ritchie et al., 2007; Li et al., 2006; Zhang et al., 2006; Martínez-Mena et al., 2012; Nosrati et al., 2015; Quijano et al., 2016). Despite these similarities between the fine and coarser scales in this case, in other cases an influence of different ecogeomorphological processes on OC redistribution at fine and coarser scales has been reported (Boix-Fayos et al., 2015).

The average TOC erosion rate in the Cárcavo watershed is low (0.031±0.03 Mg ha^{-1} y^{-1}) in comparison with the average rates reported in humid ecosystems - such as 0.07 Mg ha^{-1} y^{-1} (Smith et al., 2006) and 0.113 Mg ha^{-1} y^{-1} (Izaurralde et al., 2007) - but is closer to those reported for subhumid Mediterranean catchments (0.04 Mg ha^{-1} y^{-1} (Nadeu et al., 2015)) and is also close to the value (0.04 Mg ha^{-1} y^{-1}) that Doetterl et al. (2012) derived from the modelling of eroded pastures worldwide.

The TOC erosion/total erosion ratio in Cárcavo was lower (0.06 %) than other estimates (1-1.5 %; Boix-Fayos et al. (2009) and Smith et al. (2005)) due to the lower TOC concentration in the sediments. However, the average OC concentration of the sediments was higher than that of the agricultural soils and around half that of the forest soils of the catchment. Although the C losses from the Cárcavo watershed by erosion may seem low, they are nonetheless ecologically important and these lands must be managed to at least maintain the current soil OC level. The TOC erosion rates estimated from the data reported by Ma et al. (2016), in their study of diverse reforested areas, are similar (0.032 Mg ha^{-1} y^{-1}) to those of the Cárcavo watershed. These authors considered reforestation a less suitable choice in terms of soil loss and C sequestration. For two of our studied subcatchments (those of check-dams 10 and 7) we estimated TOC erosion rates above the average; so it seems that the impact of reforestation activities did not result in optimal and sustainable values of the TOC erosion rate.

5.2. Control of organic carbon redistribution by lateral flows

The topographical and land use characteristics of the catchment and buffer areas do not show very relevant associations with the OC pools mobilized by erosion processes and stored in alluvial sediment wedges (Table 6), as opposed to the findings in similar studies (Lacoste et al., 2015; Nadeu et al., 2015; Nosrati et al., 2015). This also differs from studies at larger scales, where soil erosion driven by land use components seems to be determinant for the TOC redistribution rates (Chappell et al., 2015).

However, the interpretation of the morphological analysis of fluvial reaches closer to the sediment wedges reveals how well-connected concave slopes with a dominance of interrill erosion processes from reforested areas closer to the fluvial channel seem to export sediment with a higher TOC concentration and with a large percentage of the MAC pool (subcatchments of check-dams 9 and 10, Table 1 and Figure 6). This resulted in higher sediment C yields or TOC erosion rates (check-dam 10, 0.56 Mg ha^{-1} y^{-1}), the highest TOC erosion/total erosion ratio, and the highest POC erosion rate (Table 3). However, fluvial reaches with irregular slope-channel connections and convex slopes close to the channel export much more sediment by concentrated and deep processes such as gully, bank, and channel erosion (check-dams 7 and 20, Figure 6), but with lower OC concentrations. This combination produced the largest sediment C yields (check-dam 7 with 0.097 Mg ha^{-1} y^{-1}; showing the lowest TOC erosion/total erosion ratio, Table 2) found among the subcatchments studied.

The OC distribution through lateral processes in the Cárcavo basin seems to be conditioned by lithological and soil factors (Table 6) and by the geomorphological processes in the channel (good correlation between Buffer_Litho_Soil and Channel, 0.73, $P<0.05$, Table 5). The source of the sediments and the erosional processes that transport sediments to the channel, as described in other Mediterranean catchments (Nadeu et al, 2011; Boix-Fayos et al., 2015), seem to play a crucial role also. The sediment dynamics described for each of the subcatchments through geomorphological mapping (Figure 6) are in agreement with the general sediment dynamics described for the whole Cárcavo basin by Sandercock and Hooke (2011). These authors performed a detailed sedimentological connectivity mapping of the Cárcavo channel and reported gully inputs and high potential supply from surrounding agricultural fields in the upstream areas of the catchment, close to the locations of check-dams 31, 16, 14, and 10. However, for the lower part of the Cárcavo channel, which lies more deeply entrenched within Quaternary alluvium and marls, the sediment supply is being sourced from adjacent valley walls (bank erosion) and gullies.

It seems that in this ecosystem with fragile conditions - namely aridity (<350 mm of rain per year), extreme events (several check-dams were washed away in the first years after installation), and erodible lithologies (high erosion rates at the subcatchment scale with a high variability, >4.5±5.5 Mg ha^{-1} yr^{-1}, data reworked from Castillo et al. (2007)) - the main control on the OC redistribution by erosion is exerted by the extreme physical conditions (erodible lithologies) and their response to rainfall events through geomorphological processes, rather than by land use and vegetation. This contrasts with findings from other environmental conditions, with more favorable climatic conditions and a denser vegetation cover: land use was found to be an important driver of C losses by erosion (Boix-Fayos et al., 2009; Lacoste et al., 2015; Nadeu et al., 2015; Nosrati et al., 2015). In the case of the Cárcavo catchment, the reforestation strategies (especially those on terraces), despite a possible increase in the SOC concentration, have not protected the soil from OC losses by active soil erosion processes.

6. Conclusions

The redistribution of OC by lateral fluxes within this semiarid watershed, especially of the MAC pool, is associated with fine particles and ^{137}Cs.

Part of this OC comes from deeper sediments mobilized by concentrated erosion processes, and some other sediments richer in OC come from vegetated (reforested) areas close and well connected to the channel. The lithology, soils, and geomorphology seem to exert an important control on the OC redistribution in this catchment, with extreme and fragile environmental conditions, more so than land use and vegetation cover.

The TOC erosion rates estimated for the Cárcavo watershed may seem low but are similar to others reported for subhumid Mediterranean catchments that are less fragile and with better conditions for vegetation growth. The TOC erosion/total erosion ratio is lower (0.06 %) than other estimates, but the average OC concentration of the sediments is higher than that of the agricultural soils and around half that of the forest soils of the catchment, indicating the difficulties in maintaining sustainable soil organic carbon contents. For ecological purposes this area should be managed to at least maintain the current levels of OC in the soils and sediments, inducing sediment sinks for OC sequestration. In this sense the connectivity of erosion processes in the landscape, losses of OC through erosion processes (even from reforested areas), and difficulties in recovering former levels of soil organic carbon in this fragile ecosystem must be taken into account when designing management approaches.

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Highlights

Catchment scale organic carbon redistribution is closely associated to fluvial sediment Dynamics, following similar patterns as ^{137}Cs and clay fractions.

The Total Organic Carbon (TOC) erosion rates for this fragile semiarid ecosystem are similar to those for subhumid catchments, less fragile and more conducive to plant growth.

The average OC concentration of the sediments was higher than that of the catchments agricultural soils, underlining the problem of maintaining sustainable soil OC contents.

Reforested areas provide large TOC erosion within the catchment by interrill erosion processes on slopes well-connected to the channel.

Lithology, soils and geomorphology exert a more important control on organic carbon redistribution than land use and vegetation cover in this geomorphologically very active environment.

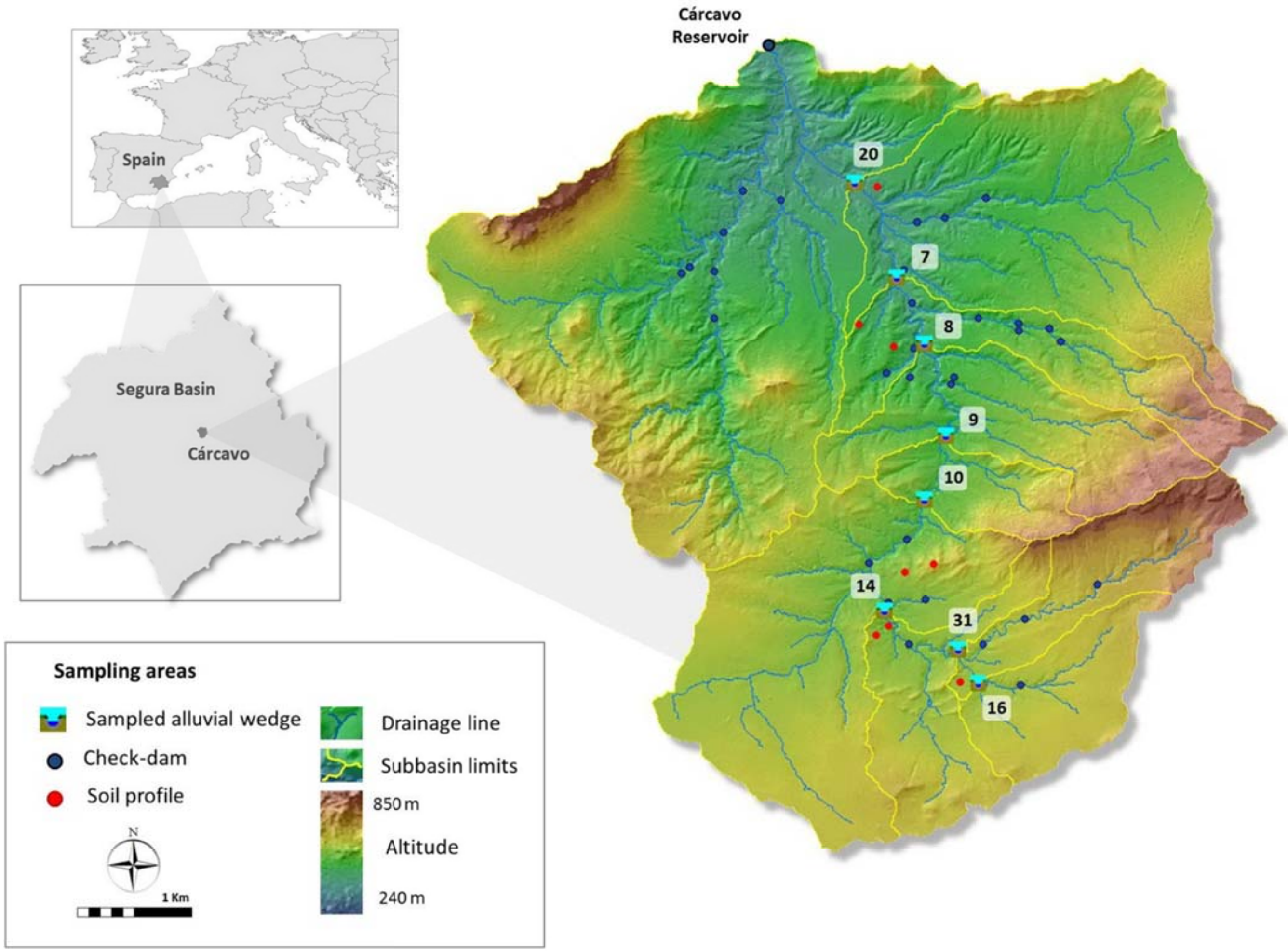

Figure 1. Location map of the Cárcavo basin

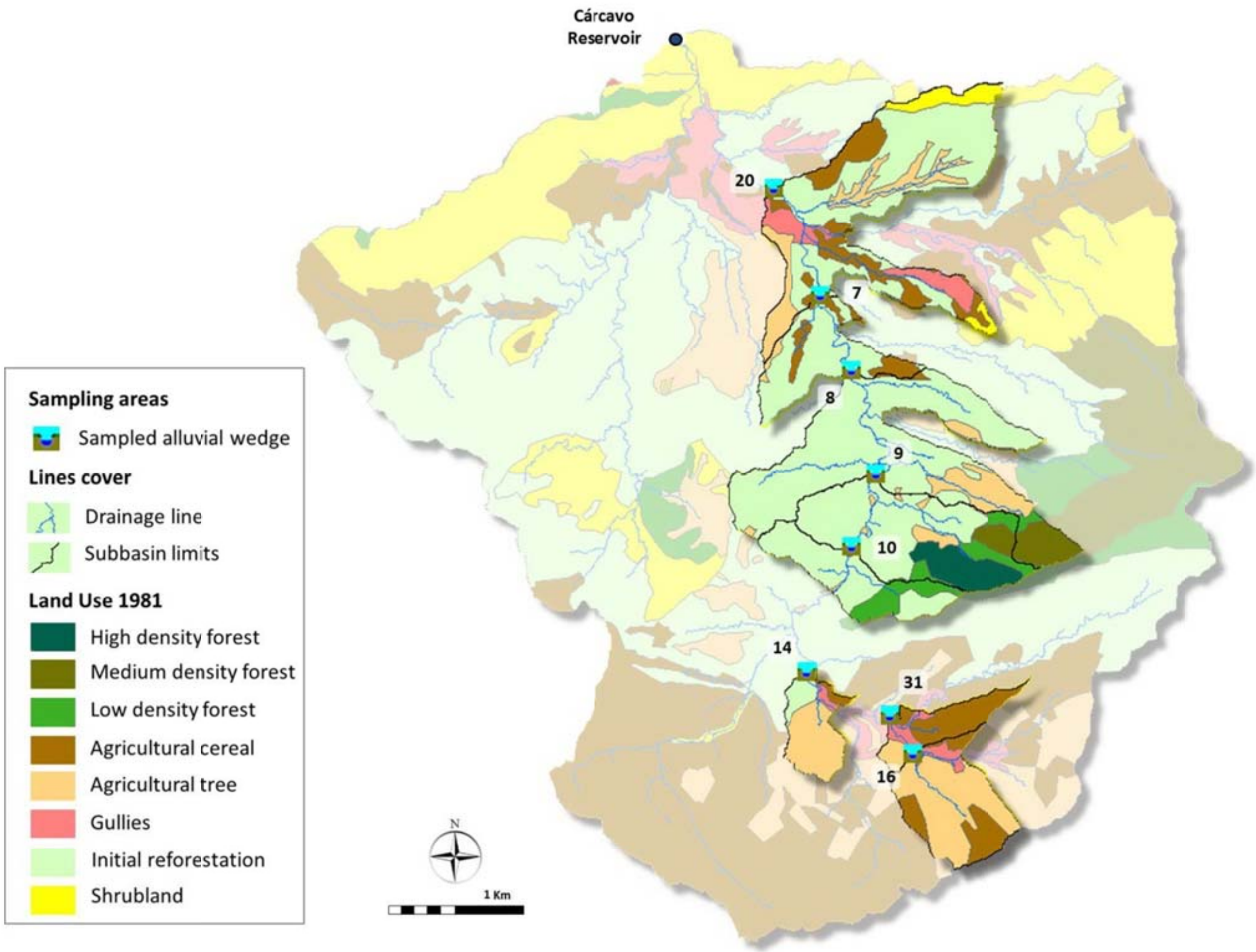

Figure 2. Land use classification at 1981, same period that check-dams construction.

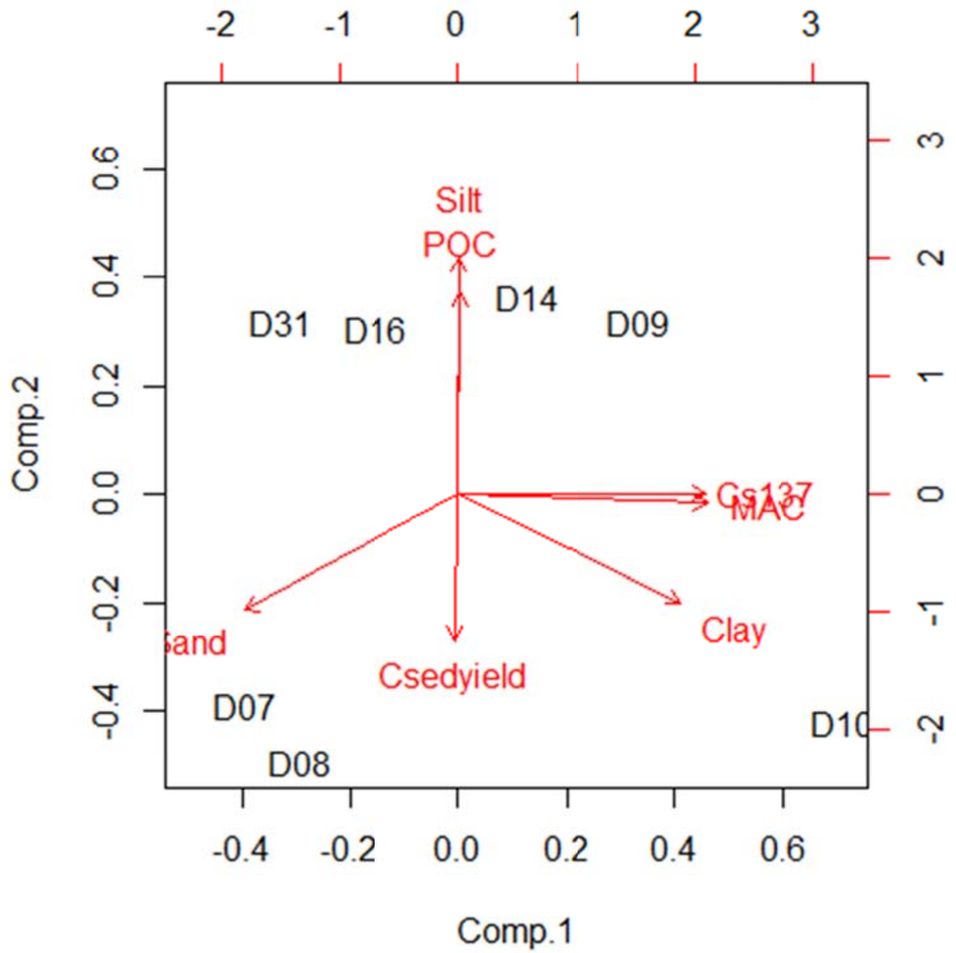

Figure 3. Bi-plot of the two first components from a PCA including textural variables, ^{137}Cs, and Carbon sediment yield in the sediment wedges. Both components explained 81% of the variance (Csedyield= TOC erosion rate).

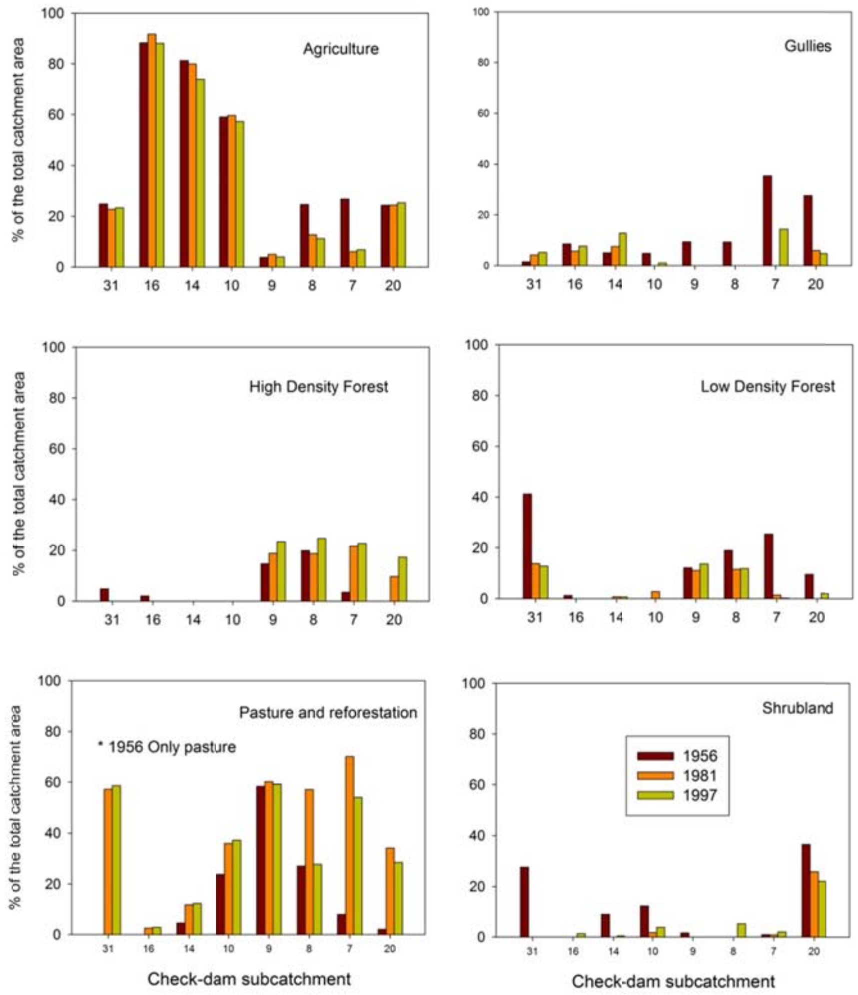

Figure 4. Land use change in the subcatchment areas of the check-dams between 1956 and 1997

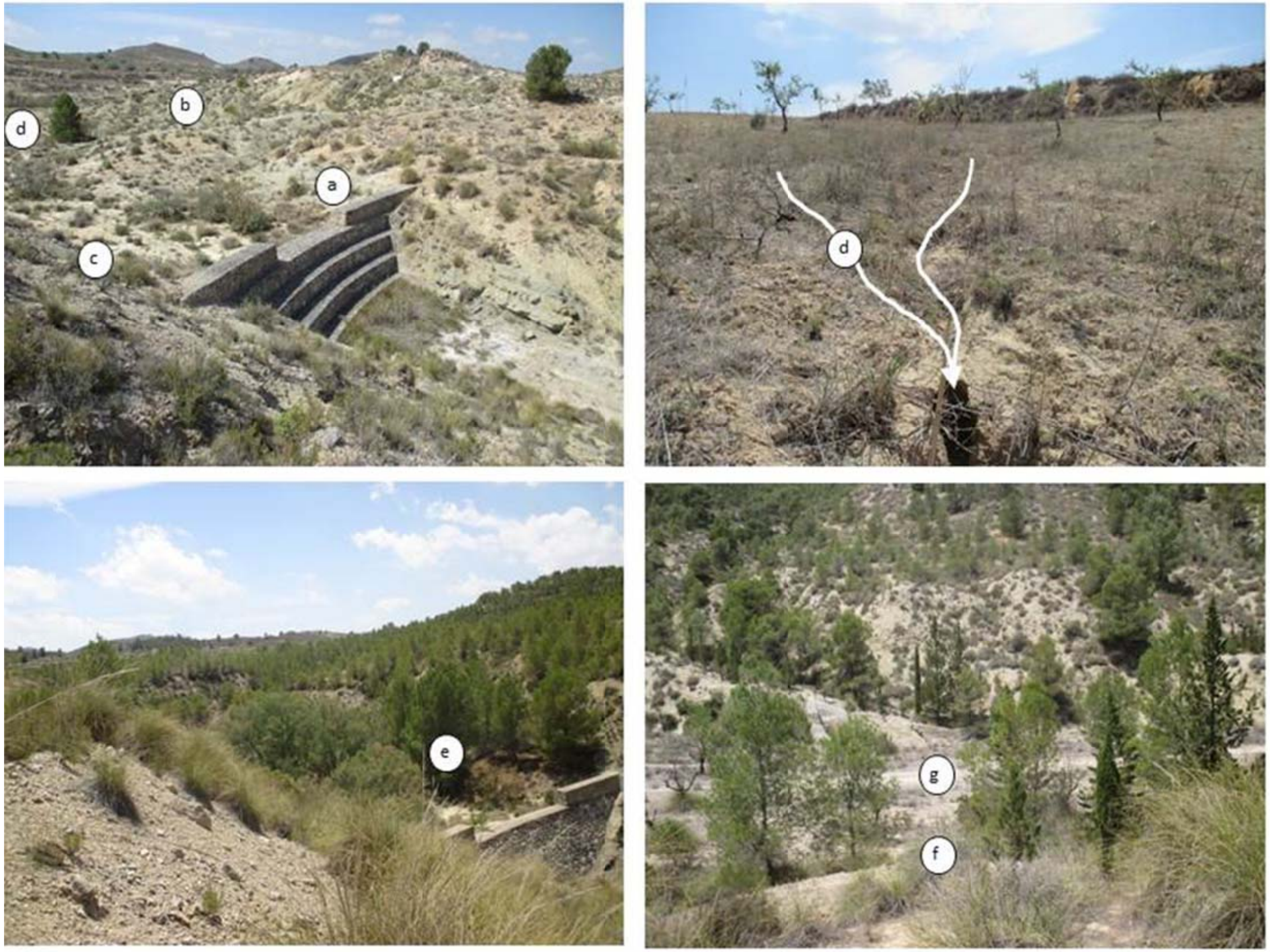
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Figure 5. Some sources of sediments to the sediment wedges of check-dams: a) bare concave slope with degraded soils connected to sediment wedge of check-dam 16; b) slopes with gullies; c) convex slope with mass movements; d) agricultural fields with ephemeral gullies; e) reforested slopes well connected to sediment wedge of check-dam 14 by interrill erosion processes; g) sediment wedge of check-dam 10; f) reforested slope with terraces connected to sediment wedge of check-dam 10 by interrill erosion processes.

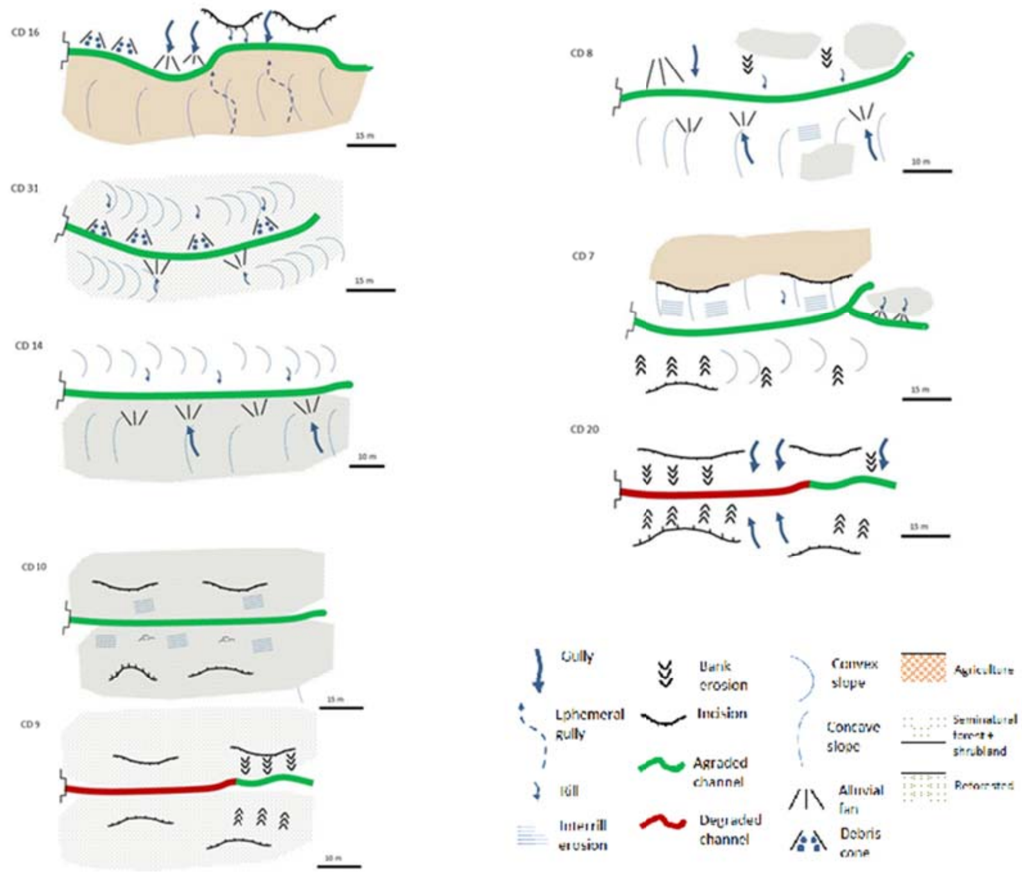

Figure 6. Morphological characterization and slope-channel connections of fluvial reaches upstream of check-dams

Table 1. Some characteristics of the subcatchment areas of the check-dams

Check-dams	Area (ha)	Altitude (m)	Slope (%)	Cu[a]	CuP[b]	CuPP[c]	NDVI	CTI[d]	Limestone (%)	Quaternary (%)	Marls (%)	Keuper (%)	Litosols (%)	Regosols (%)	Xerosols (%)
Upstream D31	155.234	510±93	35±29	0.004±9	0.050±5	0.054±4	0.20±0.11	1.6±2	17.9	14.1	66.5	1.5	61.9	30.3	7.8
D16	138.11	433±24	12±13	0.002±4	0.031±2	0.032±2	0.05±0.07	2.8±2	3.5	52.7	36.6	6.8	3.6	43.7	52.8
D14	164.968	419±30	17±17	-0.002±5	0.099±3	0.096±2	0.06±0.07	2.3±2	7.7	14.1	60.9	16.3	19.2	79.8	0.9
D10	462.117	404±23	14±15	0.000±5	0.038±3	0.038±2	0.10±0.09	2.6±2	3.5	44.5	44.3	7.7	1.9	87.8	0.2
D9	91.16	408±66	37±22	0.002±8	0.058±4	0.060±4	0.23±0.10	1.2±2	42.5	15.1	28.8	13.5	12.1	87.9	0
D8	225.293	421±102	35±25	-0.004±9	0.030±5	0.026±5	0.20±0.11	1.4±2	39.5	15.9	40.5	4.1	15.1	84.9	0
D7	186.008	414±133	38±26	0.001±9	0.014±5	0.015±5	0.21±0.11	1.3±2	13.7	18.1	62.1	6.2	8.9	84.9	6.1
Downstream D20	525.824	366±78	24±20	-0.002±7	0.025±4	0.023±3	0.18±.10	1.9±2	21.3	6.1	72.6	0	10.7	32.8	56.5
Average	244	421.9	26.5	0.000	0.043	0.043	0.15	1.9	18.4	24.9	48.5	8.0	16.7	66.5	17.7
Standard deviation	160	40.9	10.7	0.003	0.026	0.026	0.07	0.6	16.4	16.4	14.6	5.2	19.1	26.0	25.4

[a] Total curvature

[b] Planar curvature

[c] Profile curvature

[d] Compound topographic index

Table 2. Average ± standard error of texture, ^{137}Cs and organic carbon pools at the original soils and sediments from check dams

		Clay	Silt	Sand	^{137}Cs	TOC	C:N	POC	MAC	POC:MAC
		%	%	%	Bq kg^{-1}	g kg^{-1}		g kg^{-1}	g kg^{-1}	
	Soil									
	Forest	-	-	-		15.2±7.2	14.96±3.07	6.4±2.9	8.5±2.7	0.71±0.13
	Agricultural	24.07±0.58	67.1±0.14	8.81±0.69		4.4±0.9	-	-	-	
	Sediments									
	Subcatchments									
Upstream	D16	22.27±0.99	64.07±3.43	13.66±4.19	0.34	6.00±0.86	13.54±3.07	2.13±0.76	3.87±0.38	0.56±0.20
	D31	21.59±2.03	61.37±2.65	17.04±7.15	0	5.62±0.68	7.68±1.12	2.20±0.37	3.42±0.31	0.63±0.04
	D14	30.29±1.61	66.81±1.25	2.90±0.99	0.74	7.40±0.42	11.76±0.64	2.12±0.47	5.28±0.10	0.40±0.09
	D10	42.65±1.45	56.31±1.23	1.04±0.43	1.97	9.90±2.81	11.84±1.23	1.18±0.17	8.72±2.88	0.17±0.05
	D9	32.76±2.74	56.62±4.07	10.62±6.63	1.45	9.31±1.01	9.16±0.61	2.92±0.17	6.39±0.86	0.47±0.04
	D8	29.99±0.74	53.22±1.11	16.56±1.33	0	4.13±0.2	6.07±0.36	0.83±0.52	3.30±0.48	0.26±0.06
	D7	25.64±0.92	55.43±1.57	18.93±2.34	0	4.79±0.43	9.95±1.31	1.96±0.24	2.83±0.47	0.75±0.21
Downstream	D20	31.12±3.17	62.20±2.96	6.68±8.54	-	5.64±0.92	7.07±1.47	2.12±0.91	3.52±0.01	0.60±0.26
	Average	29.54±1.74	59.52±2.29	10.93±3.95		6.6±0.7	9.90±0.68	1.9±0.2	4.7±0.7	0.48±0.12

Table 3. Results of the GRCB (Generalized Randomized Complete Block) ANOVA, p values are shown (**bold** p<0.05; *italics* p<0.1)

Factor	TOC (g Kg^{-1})	Sand (%)	Silt (%)	Clay (%)
Position within the alluvial wedge	0.135	0.810	0.658	0.867
Check-dam (block)	**0.039**	*0.068*	0.154	**<0.001**
Interaction	**0.002**	0.143	**0.014**	0.220

Table 4. Total erosion, total mobilized organic carbon and pools at the different check-dams in the catchment (±standard deviation).

	Check-dam	Specific Sediment Yield (SSY) Mg ha^{-1} y^{-1}	TOC[a] erosion rate or Specific Carbon Yield (SCY) Mg ha^{-1} y^{-1}	Ratio TOC erosion/total soil erosion	POC[b] erosion rate Mg ha^{-1} y^{-1}	MAC[c] erosion rate Mg ha^{-1} y^{-1}	Ratio POC:MAC
Upstream	D16	3.59	0.018	0.005	0.0064	0.0117	0.55
	D31	1.39	0.007	0.005	0.0027	0.0042	0.64
	D14	3.44	0.023	0.006	0.0065	0.016	0.40
	D10	6.78	0.056	0.008	0.0067	0.049	0.13
	D9	0.85	0.007	0.008	0.0026	0.0049	0.46
	D8	2.78	0.010	0.004	0.0024	0.0081	0.25
Downstream	D7	23.03	0.097	0.004	0.0400	0.057	0.69
	Average	5.98±7.75	0.031±0.03	0.006±0.002	0.009±0.005	0.021±0.002	0.44±0.20

a Total Organic Carbon

b Particulate Organic Carbon

c Mineral Associated Organic Carbon

Table 5. Correlations (Spearman) between the first components of the PCA's of variables grouped by themes and scales ($p<0.05$); Subcatchment Geomorphology (Sub_Geo); Subcatchment Lithology and Soils (Sub_Litho_Soils), Subcatchment land use and vegetation (Sub_Land_Veg), Buffer (area 100 metres around check-dam) Geomorphology (Buffer_Geo),Buffer lithology and soils (Buffer_Litho_Soils), Buffer land use and vegetation (Buffer_Land_use_veget).

	Sub_Geo	Sub_Litho_Soils	Sub_Land_use_veget	Buffer_Geo	Buffer_Litho_Soil	Buffer_Land_use_veget	Channel
Sub_Geo							
Sub_Litho_Soils	-0.01						
Sub_Land_use_veget	0.42	-0.61					
Buffer_Geo	0.92	-0.30	0.62				
Buffer_Litho_Soil	-0.10	0.00	0.17	-0.12			
Buffer_Land_use_veget	0.76	0.08	0.24	0.65	0.34		
Channel	0.11	-0.08	0.47	0.00	0.73	0.30	

Table 6. Results of the stepwise multiple regression analysis to explore organic carbon pools in sediments at subcatchment scale, using as inputs the first component from PCA of grouped variables (Subcatchment Geomorphology (Sub_Geo); Subcatchment Lithology and Soils (Sub_Litho_Soils), Subcatchment land use and vegetation (Sub_Land_Veg), Buffer (area 100 metres around check-dam) Geomorphology (Buffer_Geo),Buffer lithology and soils (Buffer_Litho_Soils), Buffer land use and vegetation (Buffer_Land_use_veget).

Predicted variable	**Independent variables**	**Unstandardised partial regression coefficient ±Standard error**	**p-value**	**Multiple R^2**	**Adjusted R^2**	**F**	**p-value**
[a]**TOC (%)**	Intercept	1.051±0.044	<0.001				
	Sub_Geo	-0.03±0.029	0.37				
	Sub_Litho_Soils	-0.139±0.036	0.030	0.966	0.920	21.19	0.0154
	Sub_Land_use_veget	-0.070±0.031	0.111				
	Buffer_Litho_Soil	0.272±0.034	0.004				
[b]**POC (%)**	Intercept	1.933±0.209	0.000				
	Sub_Litho_Soils	0.242±0.156	0.171	0.287	0.168	2.418	0.170
[c]**MAC (%)**	Intercept	4.660±0.584	0.000				
	Buffer_Litho_Soil	0.9117±0.436	0.080	0.424	0.328	4.42	0.080

[a] Total Organic Carbon

[b] Particulate Organic Carbon

[c] Mineral Associated Organic Carbon