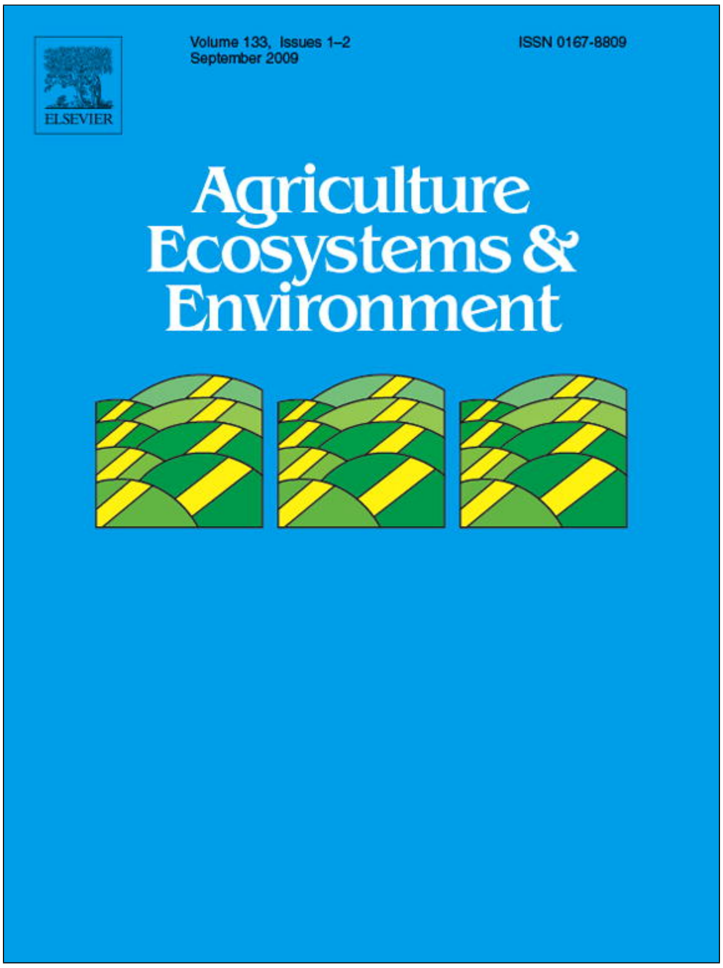
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Soil carbon erosion and stock as affected by land use changes at the catchment scale in Mediterranean ecosystems

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ABSTRACT

Catchments behave as sources or sinks of soil carbon, depending on the magnitude and type of land use changes within their drainage area, on the intensity of erosion processes and on the fate of eroded sediments. The effect of changing land uses on the organic soil carbon (C) stock and the soil C transported by water erosion and buried in depositional wedges behind check-dams was estimated in a Mediterranean catchment in SE Spain. Changes in land use patterns in the catchment between 1956 and 1997 (57% decrease in areas dedicated to agriculture and 1.5-fold increase of the total forest cover) induced an accumulation rate of total organic carbon (TOC) in the soil of 10.73 g m^{-2} year^{-1}. Mineral-associated organic carbon (MOC) was the main soil carbon pool (70%). Particulate organic carbon (POC) was highest in the shrubland soils (33%). The average sediments/soil enrichment ratio at the subcatchment scale (8–125 ha) was 0.59 ± 0.43 g kg^{-1}. Eroded soil C accounted for between 2% and 78% of the soil C stock in the first 5 cm of the soil in the subcatchments. The C erosion rate varied between 0.008 and 0.2 t ha^{-1} year^{-1}. Observed changes in land use (decrease in agricultural areas) reduced soil C erosion, although sediments from non-agricultural sources are richer in organic C. At catchment scale from the 4% of the soil C stock mobilized by water erosion, 77% is buried in the sediment wedges behind check-dams. Soil C replacement due to increased vegetation cover between 1974 and 1997 represented a 36% of the original soil organic C stock. All together represent an erosion-induced sink of soil organic C of 40% compared to the original levels of 23 years before. This has caused the catchment to behave as a soil C sink within the soil erosion subsystem since the 1950s. The meaning of this erosion-induced C sink in a wider C balance which takes into account soil respiration remains uncertain.

1. Introduction

The controversy existing within the scientific community as regards the role of water erosion in the C balance (Zhang et al., 2006) stems from the lack of agreement to whether water erosion induces C sequestration or, on the contrary, it results in a net release of C to the atmosphere. Diametrically opposed statements on the global estimations have been made: a net release of C to the atmosphere in the range of 0.37–1 pg C year^{-1} (Jacinthe and Lal, 2001; Lal et al., 2004) versus a sink of 0.56–1 pg C year^{-1} (Stallard, 1998; Harden et al., 1999; Smith et al., 2005). The last estimations defended by Van Oost et al. (2007) point to an erosion-induced sink of atmospheric C equivalent to approximately 26% of the C transported by erosion. This figure can be translated into a global C sink of 0.12 pg C year^{-1} as results of erosion in the world's agricultural landscapes (Van Oost et al., 2007). Berhe et al. (2007) estimated that the annual erosion-induced C sink offset global fossil fuel emissions of CO_2 by up to 10% in 2005. Three basic mechanisms which control the source/sink behaviour of the erosion process in relation to atmospheric C were identified by Van Oost et al. (2007): (i) the replacement of soil organic C (SOC) at sites of erosion, (ii) the burial of SOC in deposition areas and (iii) increased SOC decomposition during the detachment and transport process. Berhe et al. (2007) suggested that at erosion sites the low bulk SOC of the soil surface is replaced by subsurface material with a higher recalcitrant fraction of SOC. Furthermore, the burial of eroded sediment facilitates chemical and mineralogical transformations that contribute to C stabilization (Liu et al., 2003), although mineralization rates may be higher if the buried fraction is labile organic C (Beyer et al., 1993; Zhang et al., 2006; Mora et al., 2007).

In studies carried out at catchment scale, different results have been described. Some authors (Izaurralde et al., 2007) mention the type of agricultural land management as the principal factor that

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causes small catchments (≈1 ha) to behave as sources or sinks of organic C. However, other authors emphasize the role of rainfall characteristics and hydrodynamic processes (especially the sorting of particles during transport) rather than any effect that soil management practices may have on runoff C quality at the small watershed scale (Jacinthe et al., 2004). At larger scales (0.36–52 km^2) in semi-arid climates, Haregeweyn et al. (2008) underlined the potential of reservoirs to act as important stores of organic C in the global C balance. At a much larger scale and climatic conditions varying from semi-arid to humid in different subcatchments, Smith et al. (2005) concluded that soil erosion results in a net sink of atmospheric CO_2. Nevertheless, budgets of organic C at the catchment scale are scarce and the results diverse. As regards soil organic C erosion rates at this scale, recent published results mention 0.07 t C ha^{-1} $year^{-1}$ (Mississipi basin, direct estimations, Smith et al., 2005), 0.02–0.218 t C ha^{-1} $year^{-1}$ (Albergel et al., 2006, small semi-arid catchments, direct estimations), 0.113 t C ha^{-1} $year^{-1}$ and between 0.03 and 0.212 t C ha^{-1} $year^{-1}$ (Jacinthe et al., 2004 and Izaurralde et al., 2007, respectively, direct estimations, in small watersheds with 950 mm annual average precipitation) and 0.1 t C ha^{-1} $year^{-1}$ (Smith et al., 2007, modeled results). Of the amount of C mobilized by erosion a substantial part may be sequestered by the mechanisms described above (Van Oost et al., 2007). Sequestration rates by erosion processes have been estimated at 0.03–0.1 t C ha^{-1} $year^{-1}$ (Van Oost et al., 2005). Other authors talk about C storage rates in eroded sediments within catchments of 0.11 t C ha^{-1} $year^{-1}$ (Haregeweyn et al., 2008). These rates are lower than the recently estimated burial rates of organic C in agricultural impoundments suggested by Downing et al. (2008), who mention figures ranging from 1.48 to 170 t C ha $year^{-1}$. This implies that the world's farm ponds represent a burial rate close to the burial rate of the oceans. In recent years it has been demonstrated that sediments in depositional environments and at different spatial scales may bury substantial amounts of soil C derived from soil erosion processes, and even control atmospheric C dioxide levels on geological timescales (Galy et al., 2007).

Results also differ concerning erosion mechanisms that lead to different amounts and types of mobilized soil organic C. At the plot and slope scale, Zhang et al. (2006) found that water erosion seems to transport more of the labile fractions of SOC, which would result in higher mineralization rates in the sediments deposited by water erosion than with tillage erosion deposits. However, recent direct quantifications in the field in semi-arid conditions at plot scale (Martinez-Mena et al., 2008) suggest that the main pool mobilized by erosion is the most stable C form (mineral-associated fraction), while loss of the most labile OC fraction (particulate organic carbon, POC) was due to the cultivation effect rather than due to water erosion. In an intermediate position are the results obtained by Jacinthe et al. (2004), who attributed the mobilization of labile organic C to low intensity storms (which may be frequent in some areas), although they affirm that 75% of C mobilization occurred in high-intensity storms.

At the catchment scale, the bulk of the OC fraction is transported in the suspended sediments (Owens et al., 2002; Rhoton et al., 2006), leading to the C enrichment ratios of suspended sediment higher than 1 and C enrichment ratios of bedload sediment lower than 1 (Rhoton et al., 2006). Consequently, average C enrichment ratios (including both suspended and bedload sediment) slightly lower than 1 at the catchment scale have also been reported (Haregeweyn et al., 2008).

Another crucial process able to drastically alter the soil C stock at the catchment scale is large scale land use change. The review of Guo and Gifford (2002) pointed to a decrease of 59% in SOC due to a change from pasture to crop land. The highest losses recorded for the conversion from pasture to crops were found in areas receiving 400–500 mm of precipitation. They also found an up to 53% increase of SOC in the change from crop to secondary forest. Del Galdo et al. (2003) indicated that after 20 years of afforestation the total amount of soil C increased by a 23% in the first 10 cm of soil in humid Mediterranean conditions.

An increase of more than 50% in soil C storage was reported by Dawson and Smith (2007) after the conversion from arable to forest land. At regional scales, Vagen et al. (2005) report a decrease from 0% to 63% of soil organic C following deforestation in subhumid and semi-arid savannas. In China reductions of 10% to 40% of the soil C in cultivated soils compared with the non-cultivated soils have been reported, the soils showing the highest losses being located in the semi-arid and subhumid areas of that country (Wu et al., 2003). In Belgium a general decrease of SOC in agricultural soils and an increase of SOC in pasture soils have been detected over a period of 50 years and attributed to the changing land management (changing crops, decrease of applied manure and increase of livestock density) (Goidts and van Wesemael, 2007).

Mediterranean ecosystems, which are characterized by extreme episodic erosion events, a long history of human intervention in the landscape and drastic land use changes in the last 50 years, present a particularly interesting framework for measuring soil C changes and fluxes. Until now, few specific estimates have been made in this type of ecosystems (Del Galdo et al., 2003), especially as regards the soil erosion subsystem (Albergel et al., 2006; Smith et al., 2007; Martinez-Mena et al., 2008).

Therefore, this paper aims to: (i) report the changes in soil C stock induced by land use changes over a period of 41 years and (ii) estimate the soil C mobilized and buried in eroded sediments over a period of 27 years. Both objectives focus at catchment and subcatchment scales and in the context of typical land use changes in Mediterranean subhumid conditions.

2. Materials and methods

2.1. Study area

The study was carried out in the Rogativa catchment (province of Murcia, SE Spain, 38°08′N, 2°13′W) (Fig. 1). The catchment has a size of 47.2 km^2, with a subhumid Mediterranean climate, 583 mm of average annual rainfall and average annual temperature of 13.3 °C. The dominant lithology consists of marls, limestones, marly limestones and sandstones of the Cretaceous, Oligocene and Miocene (IGME, 1978). Mountains are mainly limestones, while mid and bottom valley locations are dominated by marls. The catchment experienced hydrological correction works in the mid 1970s, consisting of reforestation and construction of 58 check-dams. In addition the Rogativa catchment has undergone important land use changes since 1956, the forest cover increasing and the dry land agricultural area decreasing. The effect of land use changes and check-dams on the channel morphology and in the sediment yield exported at catchment scale were analysed and described in detail in Boix-Fayos et al. (2007) and Boix-Fayos et al. (2008).

Nowadays, the landscape represents a mix of dry land farming, mainly barley, plantations of walnuts (*Junglans regia*), vineyards, forests and shrublands. Soils within the catchment are described as Calcaric Cambisols and Calcaric Regosols (Ministerio de Medio Ambiente, 2001).

The forest is dominated by *Pinus nigra salzmanii*, although some *Pinus pinaster* and *Pinus halepensis* are found in the lower basin. *Quercus rotundifolia* is much reduced due to intense wood and charcoal production and clearing for agriculture. Shrublands located higher within the catchment are dominated by *Erinacea*

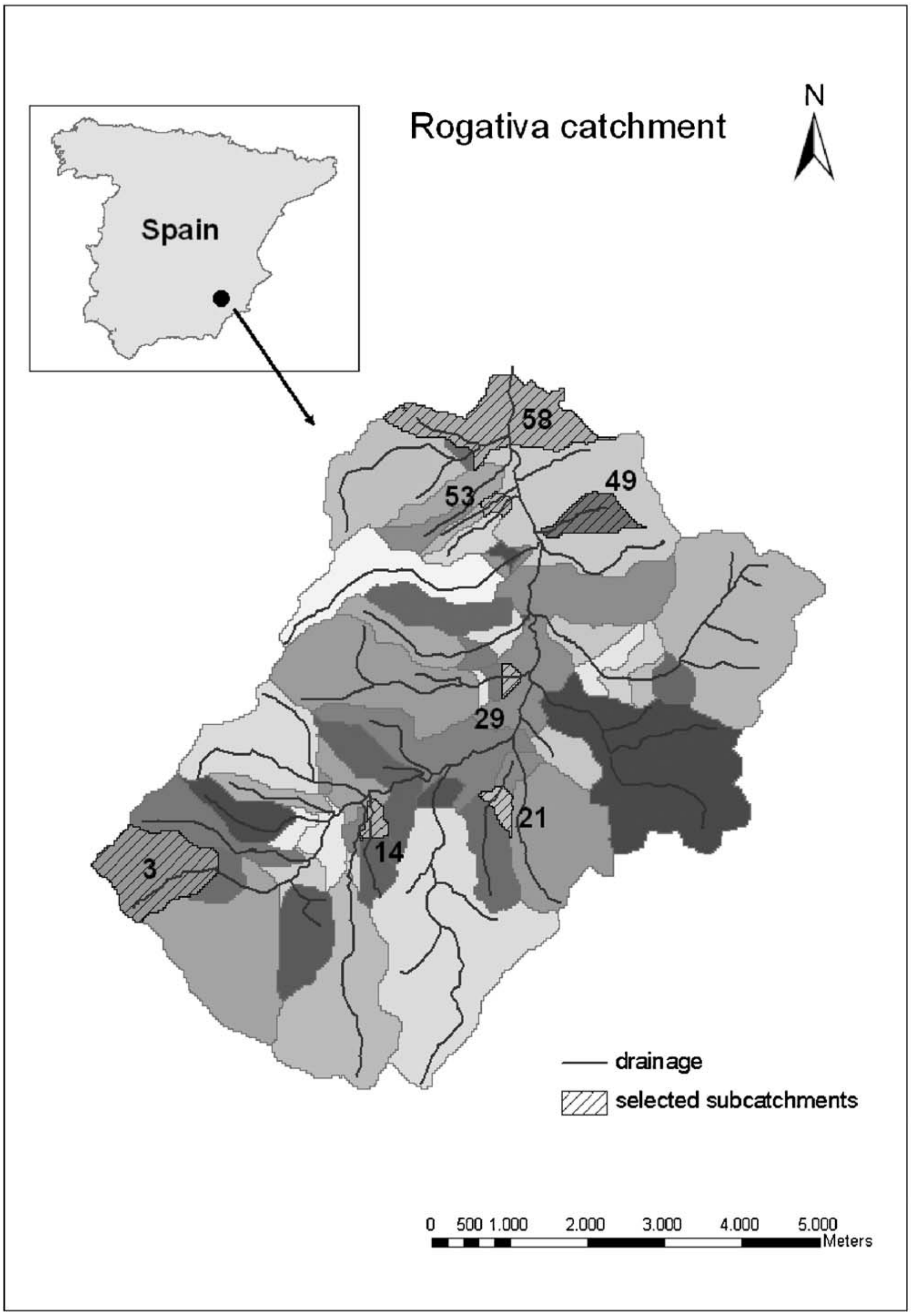

Fig. 1. Location map of Rogativa catchment, subcatchments of the check-dams installed in the basin and indication of the selected subcatchments for detailed study of erosion of soil organic carbon (subcatchments of check-dams 3, 14, 21, 29, 49, 53 and 58).

anthyllis, while at lower altitudes *Cytisus reverchonii*, *Rosmarinus officinalis*, *Thymus vulgaris* and *Genista scorpius* appear.

Soil sampling was carried out and the land use maps of 1956, 1974, 1981 and 1997 (Boix-Fayos et al., 2007, 2008) derived from previous work were used to extrapolate results at the catchment level. Seven subcatchments were selected for detailed study of eroded sediments deposited behind check-dams. The seven subcatchments (Fig. 1) are evenly distributed from upstream to downstream within the Rogativa catchment and have slightly different sizes and morphological characteristics (Table 1).

2.2. Sampling of soils

A total of 50 sampling locations distributed from upstream to downstream in the catchment were sampled at 0–5 and 5–10 cm depth. Samples were taken representing the different land uses within the catchment area of each studied check-dam (Fig. 2). Also samples were taken from areas that did not suffer land use change, as observed from a comparison of aerial photographs of 1956 and 1997. Disturbed samples for laboratory analysis and undisturbed samples for estimating bulk density of soils in rings of 100 cm^3 were taken. 30 sample locations were set up within the drainage

Table 1
Main characteristics of the selected subcatchments for detailed soil C erosion studies (average values ± standard deviation).

Catchment characteristics					Soils					Land uses 1981 (%)					
Check-dams[a]	Ravine name	Slope (°)	Catchment area (ha)	Lithology	Soil bulk Density (g kg^{-1})	TOC[c] (g kg^{-1})	%Sand[d]	%Silt[d]	%Clay[d]	D A[e]	High density forest	Medium density forest	Low density forest	Shrub[f]	Pasture
3	Umbría de l as Víboras	21.24	125.41	Marls/limestones	1.09 ± 0.10	19.21 ± 8.72	16.06 ± 5.75	61.64 ± 5.94	22.31 ± 3.48	4.51	0	45.16	47.26	3.07	0
14	Cantarrales	13.29	13.25	Limestones	0.90 ± 0.55	25.00 ± 18.48	26.13 ± 17.22	60.53 ± 17.96	13.32 ± 2.85	35.35	0	64.65	0	0	0
21	Javanas	15.03	11.42	Marls/limestones	1.02 ± 0.04	12.28 ± 5.57	25.84 ± 14.58	57.92 ± 10.28	16.23 ± 5.34	31.72	18.89	2.32	0	47.07	0
29	Escribano	12.04	7.92	Limestones/sandstones	1.04 ± 0.05	18.55 ± 9.94	38.29 ± 22.06	52.31 ± 19.13	9.40 ± 3.62	67.18	0	0	32.82	0	0
49	Casa Nueva	17.57	123.67	Marls	1.06 ± 0.05	13.78 ± 6.59	20.68 ± 6.25	61.26 ± 6.23	18.05 ± 2.32	20.31	0	2	28.94	48.75	0
53	Ermita	10.95	9.375	Marls/limestones	1.00 ± 0.33	16.43 ± 6.07	23.69 ± 5.22	61.93 ± 6.33	14.41 ± 2.49	20.20	19.80	0	0	0	0
58	Rogativa	15.34	146.96	Marls/limestones/ sandstones	1.19 ± 0.09	10.36 ± 4.76	35.69 ± 13.19	51.20 ± 13.23	13.14 ± 4.97	8.98	7.90	54.49	1.94	13.49	13.19

[a] Subcatchment characteristics belonging to the indicated check-dams.
[b] 0–5 cm.
[c] Total organic carbon in the soil (0–10 cm).
[d] 0–10 cm.
[e] Dry land agriculture.
[f] Shrubland.

areas of the studied check-dams and the rest in different subcathments within the Rogativa catchment.

2.3. Sampling of deposited sediments

A field survey to estimate the volume of sediments trapped by all the check-dams within the catchment (58) was carried out. Seven subcatchments corresponding to the check-dams numbers 3, 14, 21, 29, 49, 53 and 58, evenly distributed within the catchment, were selected for more specific soil C erosion studies. All check-dams were georeferenced with a GPS Trimble GeoXM with differential correction. Furthermore, the dam structure (height, length) was recorded, and detailed mapping of the sediment wedges behind each dam was carried out. The volume of sediments was estimated assuming that the alluvial wedge had the form of a prismatic channel with a rectangular section (Castillo et al., 2007); the height and area of the wedges were measured of the seven selected subcatchments, undisturbed samples were taken of the retained sediments behind the check-dams to estimate the average bulk densities and the organic C content. The sediment wedges were sampled at the front and the end of the wedge (two sampling areas per wedge). Bulk samples of 100 cm^3 at 7 cm depth intervals were taken to a maximum depth of 1.25 m, and two replicates at 7 cm depth intervals to 35 cm depth were taken at each sampling site. A total of 189 undisturbed samples were collected. Knowing the volume of sediments trapped and the average bulk density of the sediment at each alluvial wedge, the mass of sediment retained by each check-dam was calculated. Specific sediment yield data (SSY, t ha^{-1} $year^{-1}$) and absolute sediment yield (SY, t $year^{-1}$) were assessed based on the volume of sediments retained by each check-dam, the bulk density of sediments, the trap efficiency of check-dams and the drainage area of each check-dam. Trap efficiency for each check-dam was calculated following Brown (1943), using the initial volume of each check-dam. This method estimates trap efficiency according to the structure capacity and watershed area ratio and is useful for estimating of mid- and long-term trap efficiencies, especially when no inflow data area available (Verstraeten and Poesen, 2000).

2.4. GIS analysis

GIS analysis was used to derive various catchment characteristics. First of all, the catchment area draining to each check-dam and the average slope were calculated using a Digital Terrain Model (DTM) of the catchment at 5 m spatial resolution. The land use pattern of the catchment was mapped from aerial photographs of 1956, 1981 and 1997, as reported previously in Boix-Fayos et al. (2007). Furthermore, a Landsat MSS image of 1974 was classified to obtain a land use map of 1974 (Boix-Fayos et al., 2008). With the detailed analysis of aerial photographs the following classes could be mapped: high density forest, medium density forest, low density forest, shrubland, pasture land and dry land agriculture. From the satellite image, with its much poorer spatial resolution than the aerial photographs (1 m and 60 m, respectively), areas of the high and medium density forest were merged. The spatial data were available for the whole catchment and specific data on the selected subcatchments were extracted from this spatial data base. Because of the lower spatial resolution of the satellite imagery, the land use map of 1974 was used to extrapolate the results of this study at the catchment scale and not for the more detailed analysis at the subcatchment scale.

GIS procedures were also used to characterize the land use pattern for 1956, 1981 and 1997 in each subcatchment by application of the perimeter to area ratio and the fragmentation

Fig. 2. View of the subcatchment of the Casa Nueva ravine (check-dam 49) with examples of land uses and erosion features. (1) Dry land agricultural terraces with cereals; (2) Shrubland; (3) Medium density forest; (4) Low density forest; and (5) Bank erosion in the main channel of the Rogativa catchment.

index (Monnomier, 1974, Eq. (1)):

$$F = \left(\sum_{i=1}^{m}\left(\frac{c-1}{n-1}\right)/n\right) \qquad (1)$$

where n: number of different classes present in the kernel of 5 by 5 pixels, c: number of cells considered in the 5 by 5 pixels kernel, and m: number of pixels in the image. A high perimeter to area ratio and a high fragmentation index point to a more fragmented land use pattern with more small isolated patches of different land uses.

2.5. Laboratory methods

Particulate organic carbon (POC) and total organic carbon (TOC) of soils were directly determined in the following way: POC was separated from the TOC by wet sieving (Cambardella and Elliott, 1992). 20 g of dry mineral soil (<2 mm) were dispersed by shaking overnight in a 100 ml solution of sodium hexametaphosphate (5 g l^{-1}). The mixture was then sieved through a 0.053 mm sieve. The POC was recovered by back-washing the sieve followed by filtration (Whatman filter paper #541). POC consisted of free organic debris and some larger fragments of organic matter released by the dispersion of soil aggregates. This POC fraction was weighed after oven drying (60 °C), ground using a mortar and stored for carbon analysis. Organic C from the POC fraction (2–0.053 mm) and TOC fraction (<2 mm) was determined by wet oxidation using a hot mixture of 1 N potassium dichromate and concentrated sulphuric acid, following Yeomans and Bremmer (1989).

Sediment samples collected at each alluvial wedge of the studied check-dams, were air-dried, sieved at <2 mm and ground. TOC was determined by Yeomans and Bremmer (1989) described above.

Soil C in the POC or TOC fraction (g C g^{-1} soil) was calculated by multiplying the dry mass of each part (g part g^{-1} soil) by the respective C concentration (g C g^{-1} part). Mineral-associated carbon (MOC) was estimated by the difference between TOC and POC

For the texture analysis, soil samples were air-dried; the organic matter was eliminated with H_2O_2, the samples were chemically dispersed with hexametaphosphate and their particle size distribution was characterized by laser diffraction using a Coulter LS200. Three laboratory replicates for each sample were made. The percentage of coarse and fine sand, coarse and fine silt and clay were obtained as well as the geometric mean size of particles.

2.6. Estimation of C stock, eroded C and statistical analysis

Based on the soil sampling, the C stock at each specific site (t ha^{-1} or g m^{-2}) was calculated as the product of C concentration (g kg^{-1}), soil bulk density (g cm^{-3}) and soil depth (cm).

Extrapolation of C stock for the soils of a whole subcatchment (t) was estimated as the sum of the products of the area of each land use within the subcatchment (ha), the soil sampling depth (cm), soil bulk density (g cm^{-3}) at each land use and soil C concentration (g kg^{-1}).

Estimation of eroded C at the subcatchment scale was based on the sediment sampling and the estimated sediments retained by the check-dam in each subcatchment (corrected by the trap efficiency to obtain the eroded sediment). The eroded C was calculated as the product of the mass of eroded sediment (kg) and sediment C concentration (g kg^{-1}) related to the drainage area and time units to calculate the soil C erosion rates (t C ha^{-1} $year^{-1}$).

Extrapolation of eroded C at catchment scale was estimated as the product of retained sediments by all the check-dams within the catchment (58 in total, corrected by the trap efficiency to obtain the eroded sediment) and average sediment C concentration (g kg^{-1}) of the seven sampled alluvial wedges. This was related to the soil C stock of the first 5 cm of soil in the whole catchment with the land use pattern of 1974 and 1997.

Differences in soil C content among between land uses were explored using a single way analysis of variance and Tukey's honest significant difference test for post-hoc comparisons. The associations between TOC in soils and sediments and subcatchment characteristics (average slope, soil texture, drainage area, land use at different years, land use changes between years, fragmentation indices of each land use for different years, and the perimeter to area ratio of each land use for different years) were explored using Spearman correlation tests.

3. Results and discussion

3.1. Soil C stocks following land use changes at catchment scale

The TOC, POC and MOC concentrations and stocks for the different land use classes identified in the Rogativa catchment are shown in Table 2 and Fig. 3. As can be seen, the TOC concentration

Table 2
Average values and standard deviations of TOC, POC and MOC concentrations in soils (0–10 cm) under different land uses with indication of significant differences.

Land use	TOC (g kg^{-1})[d]	POC (g kg^{-1})[e]	MOC (g kg^{-1})[f]	Ratio area[g] (ha) 1981/1956	Ratio area (ha) 1997/1981	Ratio area (ha) 1997/1956
High density forest	28.17 ± 18.61^{a}	8.91 ± 3.94^{a}	19.65 ± 13.07^{a}	3.39	1.80	6.12
Medium density forest	25.89 ± 19.32^{ac}	7.84 ± 7.02^{ac}	14.61 ± 6.25^{ab}	0.54	1.27	0.69
Low density forest	18.37 ± 9.06^{abc}	4.46 ± 2.14^{abc}	13.90 ± 6.28^{ab}	1.02	1.48	1.52
Total forest	–	–	–	1.51	1.47	2.22
Shrubland	14.97 ± 5.08^{abc}	4.91 ± 2.47^{abc}	10.05 ± 4.27^{ab}	0.46	1.00	0.46
Pasture land	15.22 ± 8.09^{abc}	3.62 ± 1.79^{abc}	11.60 ± 7.35^{ab}	1.68	0.32	0.54
Dry land agriculture	8.12 ± 3.20^{b}	1.57 ± 1.02^{b}	6.55 ± 2.77^{b}	0.75	0.57	0.43

[abc] Different letters in the subscript indicate significant different values according to Tukey's HSD test.
[d] Total organic carbon.
[e] Particulate organic carbon.
[f] Mineral-associated organic carbon.
[g] Ratios of the areas covered by the different land uses between the indicated years.

is highest in the high density forest soils and lowest in the dry land agricultural soils (28.17 ± 18.61 and 8.12 ± 3.20 g kg^{-1}, respectively). The TOC concentration in high density forest soils is 1.88 times the concentration in shrubland soils and 3.47 times the concentration in agricultural soils. TOC and POC concentrations are significantly higher in soils under high density and medium density forest than in agricultural soils, but not in the rest of land use classes (Table 2). MOC concentrations are significantly higher in soils under high density forest than in agricultural soils. The TOC stock in the soil gradually decreases from the high density forest, to the low density forest, followed by pasture, shrubland and dry land agricultural soils. The values vary between 1419 ± 896 and 457 ± 201 g m^{-2} for high density forest and agricultural soils, respectively (Fig. 3). These values are within the range of values estimated for other areas in the same region (Martinez-Mena et al., 2008).

The MOC is the main pool of soil C for all land uses, the dry land agricultural soils having the highest MOC pool (80%) and the shrubland soils the lowest (67%). The POC pool represents between the 20% and the 33% of the TOC in the dry land agricultural and shrubland soils, respectively (Fig. 3).

The total stock of TOC, POC and MOC in the soils for the whole catchment of the Rogativa was assessed by extrapolation of the measured average values per land use class to the land use pattern mapped for 1956, 1981 and 1997. The results are presented in Table 3. The soil TOC stock increased gradually between 1956 and 1997, as did the POC and MOC pools. This increase was parallel to the change in the land use pattern between 1956 and 1997: a 0.43-fold decrease (−57%) in agricultural areas, a 1.5-fold increase in the total forest cover, and a particularly large increase in the high density forest of 6.12-fold (Table 2). In general, the estimated rate of TOC accumulation for the Rogativa catchment between 1956 and 1997 is 10.73 g C m^{-2} year^{-1} and the estimated rate of POC accumulation for the same area in the same period is 3.19 g C m^{-2} year^{-1}. The TOC accumulation rate is lower than that reported by Post and Kwon for changes from agriculture to forest and pasture (33.8 and 33.2 g C m^{-2} year^{-1}, respectively) taken as average for a wide range of environmental conditions. The TOC accumulation rate for Rogativa shows a value within the range reported by Vagen et al. (2005) from humid, subhumid and semi-arid savannas (7–12 g C m^{-2} year^{-1}) and slightly higher than the rates of C loss with changes from forest to agriculture in a semi-arid area in SE Spain (Martinez-Mena et al., 2008).

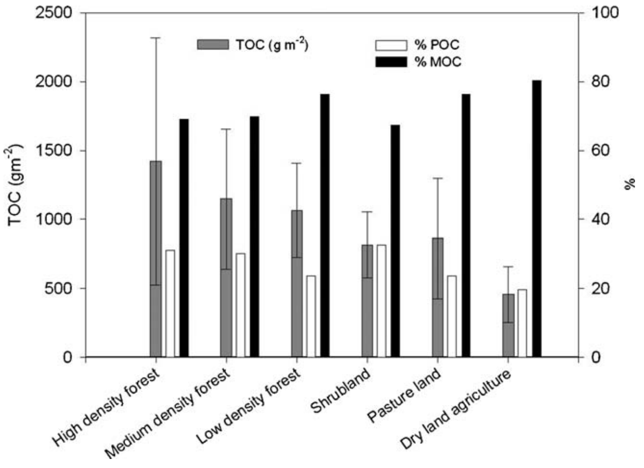

Fig. 3. TOC (g m^{-2}), standard deviation and corresponding percentage of POC and MOC (0–10 cm soil depth) determined for each land use class.

In general, the change from dry land agriculture to forest represents a gain of 71% of TOC in the soil, much higher value than the increase of 23% reported by Del Galdo et al. (2003) for soils in Northern Italy in very humid conditions and the 53% reported by Guo and Gifford (2002) in a meta-analysis of data on land use change for different regions. The changes from forest to shrubland, from shrubland to dry land agriculture and from pasture to dry land agriculture were all around a decrease of 46% of soil TOC in the Rogativa catchment, which is within the range of values reported by Guo and Gifford (2002), losses of 42% from forest to crop and 59% from pasture to crop.

In general, following the changes experienced in the land use pattern of the Rogativa catchment the gain in soil C has been high compared with other published data but within the range of accumulation rates found for semi-arid and subhumid areas.

3.2. Total organic C buried in sediments and land use change

The TOC buried in the sediments deposited behind check-dams is shown in Fig. 4 at the different sampling depths and in two positions within the wedge of sediments, at the front (close to the wall of the dam) and at the end of the wedge.

The TOC concentration in the sediments varies from 0.7 to 35.16 g kg^{-1} with an average of 9.61 g kg^{-1}. Depending on the subcatchment, substantial differences in depth variations in TOC can be observed. Such variations were assessed from three indicators: the standard deviation, the variance and the coefficient

Table 3
Extrapolation of the TOC and POC stocks (0–10 cm) to the land use patterns of 1956, 1981 and 1997 at the Rogativa catchment.

	Stock (g m^{-2})		
	1956	1981	1997
TOC[a]	1811	1899	2251
POC[b]	450	498	581

[a] Total organic carbon.
[b] Particulated organic carbon.

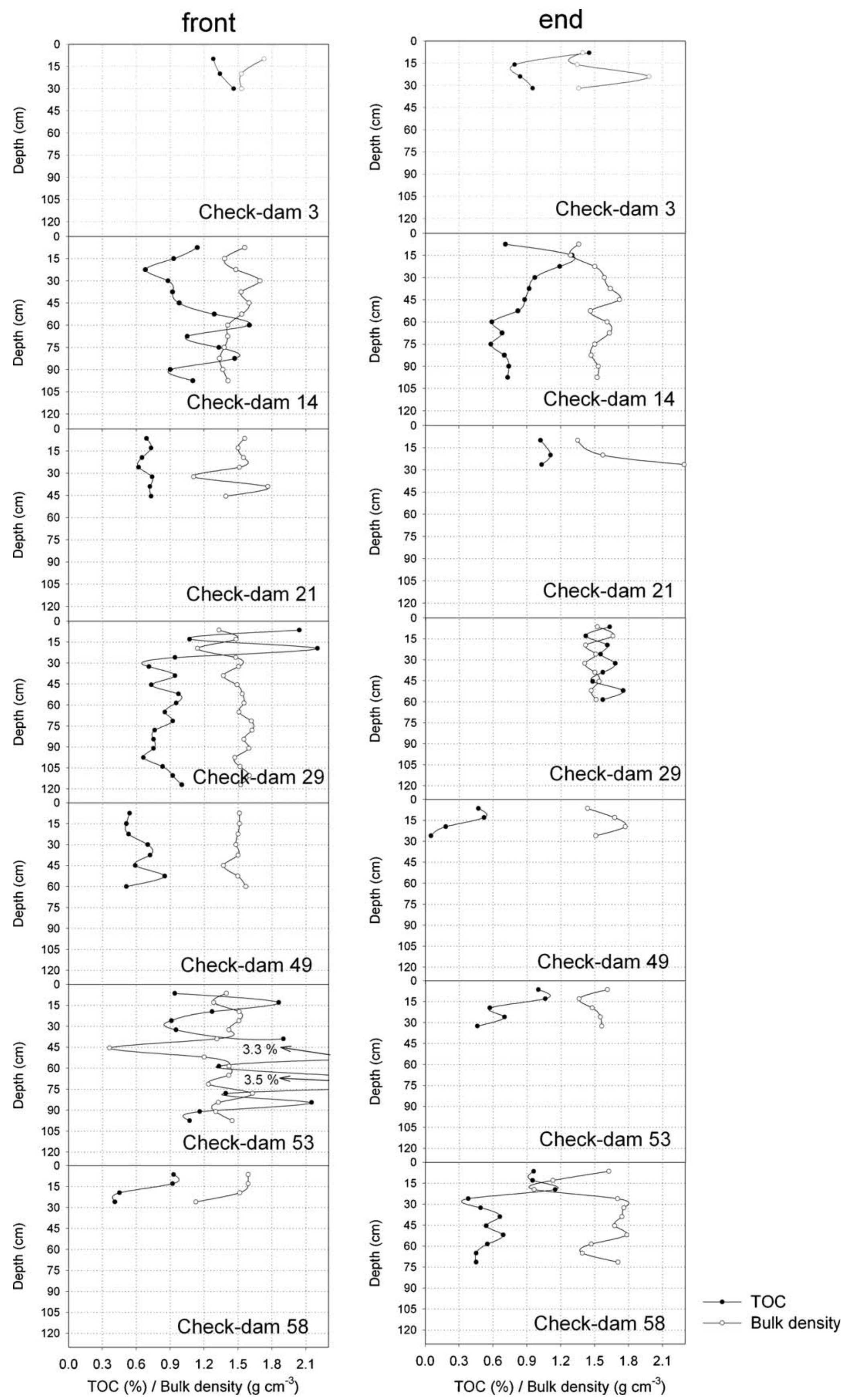

Fig. 4. TOC in sediments (%) and bulk density of sediments at different depths in the alluvial wedges of some check-dams. Two positions within each alluvial wedge were sampled: front (close to the check-dam wall) and end (at the end of the alluvial wedge upstream).

Table 4
Significant correlations between land use, land use change variables, slope and an indicator of variation of TOC in buried sediments.

	%Shrubland 1956	%Pasture 1956	%Decrease DA[b] 1981–1997	Fragmentation index 1981[c] DA[b]	Fragmentation index 1981 MDF[d]	Slope (°)
STD of TOC in buried sediments[a]	−0.644 $p = 0.013$	−0.601 $p = 0.023$	+0.762 $p = 0.002$	0.675 $p = 0.008$	0.732 $p = 0.039$	−0.673 $p = 0.008$

[a] Standard deviation of TOC concentration in depth of sediments buried behind check-dams (the depth of the sediments was different within sampling points at each dam, varying between 0–27 and 0–125 cm).

[b] Dry land agriculture.

[c] The fragmentation index of the land use pattern of each subcatchment was calculated for 1981. These are the earliest available detailed photographs that were taken only 5 years after the instalation of the check-dams (1976).

[d] Medium density forest.

of variation of TOC in the different sampled depths in each sediment wedge. The sediments retained by check-dams 3, 14 and 49 showed the lowest coefficient of variation of TOC in depth (0.1, 0.22 and 0.28, respectively). Check-dams 3 and 49 showed lower standard deviations of TOC in depth (1.45 and 1.55 g kg^{-1}, respectively). These subcatchments seem to have suffered only minor modifications of their land use pattern (area and distribution of land uses) between 1956 and 1997 compared with the other subcatchments.

Only the standard deviation of the TOC in buried sediments showed significant correlations with other catchment characteristics and indicators of land use and land use change (Table 4). The negative correlation between the shrubland and pasture cover of 1956 and the variation of TOC in depth (−0.644 $p = 0.013$; −0.601 $p = 0.023$, respectively) might be attributed to subcatchments with a large and homogeneous cover of shrubland and pasture undergoing a regular mobilization of TOC in the eroded sediments. In contrast, a positive correlation between the decrease in dry land agricultural area between 1981 and 1997 and variations of TOC in depth of buried sediments (+0.762 $p = 0.002$) is attributed to the substitution of agricultural areas by other land uses, indicating a variation of the sources of sediment or of the erodibility of soils, which led to the mobilization of sediments with different characteristics.

The negative relation between slope and variation of TOC in depth in buried sediments can be explained by the fact that steeper slope gradients facilitated a continuous flow, better hydrological connectivity with a lower degree of sediment deposition in the runoff track until final deposition behind the check-dam. Also, the subcatchments showing the least variation in land use pattern had the highest average slope. So, this factor could be related to the fact that a lesser degree of land use change results in limited or no change in the sediment sources, which provide sediments with stable TOC concentrations over time. This can be seen in the sediments corresponding to different events buried in the alluvial wedges.

In contrast, the positive correlation between the fragmentation indices of dry land agriculture and medium density forest in 1981 and the variation of TOC in buried sediments are attributed to the enrichment of TOC in sediments in catchments with more fragmented land uses.

3.3. Enrichment ratios of soil C in sediments

The enrichment sediments/soil ratios (ER) of each studied subcatchment for bulk density, TOC concentration and texture variables are shown in Table 5. Enrichment ratios for the TOC concentration vary between 0.35 and 0.89, with an average of 0.59 ± 0.43. These enrichment ratios are lower than most of those reported in the literature referring to recently exported sediments due to water erosion at finer scales (plot scale) (Owens et al., 2002, ER = 1.5 in small watersheds <0.8 ha; Quinton et al., 2006 ER = 2.6–4.5 in plots 25 m × 30 m; Martinez-Mena et al., 2008, ER = 1.91–2.38 in plots 8 m × 2 m). Rodriguez-Rodriguez et al. (2004) also reported a relatively low enrichment ratio (0.97) in erosion plots of 200 m^2 in Andosols. At the catchment scale Rhoton et al. (2006) reported higher enrichment ratios for suspended sediment (2.13) and lower for bedload (0.65). The C concentrations of the sediments estimated in the Rogativa catchment correspond to sediments buried over a period of 27 years (the check-dams that retain the sediments were installed in 1976). C oxidation, even at a low rate, has probably taken place during this time. The sediments retained by the check-dams include suspended and bedload sediments. Sediments may originate from superficial soil horizons through sheet and rill erosion but also from deeper soil layers removed by gully erosion. All these factors result in a lower ER than that derived from measurements at finer spatial and temporal scales (event-based). Also a low enrichment ratio of organic C (0.93) is found by Haregeweyn et al. (2008) in sediments of small reservoirs for similar environmental conditions and scales, comparable to our study area.

The exported sediments are slightly enriched in clay and sand particles (1.17 ± 0.42 and 1.12 ± 0.47, respectively). Although no significant correlations between enrichment ratios of TOC and enrichment ratios of the different textural classes appear, the subcatchment with the highest TOC enrichment ratio (0.89) shows also the highest clay enrichment ratio (2.47) (Table 5).

3.4. Soil C mobilized by water erosion at the subcatchment and catchment scale

TOC mobilized by water erosion at the studied subcatchments was estimated (Table 6) and compared with the total erosion and the TOC stock in the upper 5 cm of soil. This estimation is based in the land use pattern of each subcatchment extracted from the

Table 5
Average enrichment ratios sediments/soil ± standard deviations at each studied subcatchment of some measured variables.

Subcatchments	Bulk density (g cm^{-3})	TOC (g kg^{-1})	Sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)
Check-dam 3	1.46 ± 0.12	0.62 ± 0.33	0.75 ± 0.19	1.15 ± 0.14	1.01 ± 0.10	1.13 ± 0.17
Check-dam 14	2.10 ± 1.28	0.35 ± 0.20	1.52 ± 0.25	1.29 ± 0.05	0.75 ± 0.11	1.07 ± 0.32
Check-dam 21	1.49 ± 0.06	0.80 ± 0.57	1.14 ± 0.92	0.74 ± 0.08	0.65 ± 0.20	0.78 ± 0.30
Check-dam 29	1.51 ± 0.07	0.89 ± 1.06	0.59 ± 0.31	1.46 ± 0.94	1.79 ± 1.18	2.47 ± 1.48
Check-dam 49	1.61 ± 0.07	0.41 ± 0.22	1.62 ± 0.61	1.04 ± 0.13	0.89 ± 0.13	0.87 ± 0.14
Check-dam 53	1.72 ± 0.83	0.60 ± 0.33	1.04 ± 0.32	1.18 ± 0.12	0.81 ± 0.33	1.07 ± 0.29
Check-dam 58	1.30 ± 0.11	0.43 ± 0.29	1.17 ± 0.67	0.62 ± 0.19	0.68 ± 0.20	0.81 ± 0.28
Average	1.60 ± 0.36	0.59 ± 0.43	1.12 ± 0.47	1.07 ± 0.24	0.94 ± 0.32	1.17 ± 0.42

Table 6
TOC mobilized by water erosion, total erosion and organic C stock of the original soils at the subcatchment scale.

Subcatchments	TOC stock (upper 5 cm of soil) (t)[a]	TOC mobilized by water erosion[b] (t)	TOC buried in sediments (t)	TOC storage rate[c] (t ha^{-1} year^{-1})	TOC erosion rate (t ha^{-1} year^{-1})[c]	Ratio TOC erosion/total soil erosion[d]	%Eroded TOC of the original soil[e]
Check-dam 3	1494.23	26.39	11.69	0.003	0.008	0.0121	1.76
Check-dam 14	132.67	11.30	10.11	0.002	0.032	0.0095	8.52
Check-dam 21	95.14	12.28	11.26	0.038	0.041	0.0106	12.91
Check-dam 29	52.95	41.04	40.18	0.195	0.199	0.0120	77.51
Check-dam 49	621.50	13.44	7.70	0.002	0.004	0.0046	2.16
Check-dam 53	120.51	20.60	19.66	0.081	0.085	0.0118	17.10
Check-dam 58	1665.00	185.57	174.99	0.048	0.051	0.0071	11.14

[a] Total organic carbon estimated with reference samples taken within the subcatchments at sites with no land use change between 1956 and 1997.
[b] Total organic carbon calculated by estimation of the weight of sediments retained behind each check-dam and corrected by the trap efficiency (according to Brown, 1943) of each check-dam.
[c] Total organic carbon in sediments retained by check-dams.
[d] Following Smith et al. (2005).
[e] Percentage of eroded TOC in relation to the soil carbon stock at each subcatchment area in 1981, after installation of check-dams between 1976 and 1977.

Table 7
Correlations (Spearman) between variables indicating eroded TOC and some characteristics of the subcatchment areas.

	TOC[a] sediments (g kg^{-1})	Eroded TOC (t ha^{-1} year^{-1})	Eroded TOC (t)	Buried TOC in sediments (t)	%Eroded TOC with respect to the stock in soils
Coarse silt (%)	–	–	−0.865 $p = 0.012$	–	–
Drainage area (ha)	–	–	–	–	−0.786 $p = 0.036$
Slope (°)	–	−0.786 $p = 0.036$	–	–	−0.857 $p = 0.014$
Erosion (t ha^{-1} year^{-1})	–	–	–	–	0.893 $p = 0.007$

[a] Total organic carbon.

aerial photograph of 1981, 4 and 5 years after the installation of the check-dams (aerial photographs of the same period of the installation of check-dams were not available and the land use derived from the 1974 satellite image had much poorer spatial resolution). The highest SOC stock appears in the largest catchment areas (check-dams 3 and 58). The highest total C mobilized by water erosion and buried in sediments is also found in the subcatchment with the largest catchment area (check-dam 58). The average soil C erosion rate for the studied subcatchments is 0.06 t ha^{-1} year^{-1} while the highest TOC erosion rates are found in the smallest subcatchments (check-dam 29, check-dam 53) (Table 6). The highest percentage of eroded TOC with respect to the TOC stock in the catchment area are also observed for the smallest subcatchments as were the highest the ratios of TOC erosion/total erosion. The catchment of check-dam 3 with the highest percentage of forest cover also shows a high TOC erosion/total erosion ratio. The ratios of TOC erosion to total erosion oscillate from 0.0046 to 0.0121, which are lower than the ratios reported by Smith et al. (2005) for several subcatchments of the Mississipi basin (from 0.0093 to 0.0233) mainly dedicated to agricultural use. However, these ratios are very significant when related to the soil C stock of the catchment. The percentage of TOC erosion with respect to the C stock of the original soil varied from 1.76% to 77.51%, suggesting that in catchments with a low soil C stock, erosion processes may represent an important output of soil C. A significant negative correlation exists between the percentage of eroded TOC and drainage area and slope, respectively (Table 7). In the smallest catchments, the eroded TOC easily reaches the

Table 8
Correlations (Spearman) between variables indicating eroded TOC, land use and land use pattern variables of the subcatchments.

	TOC sediments (gkg^{-1})	Eroded TOC (t ha^{-1} year^{-1})	Eroded TOC (t)	Buried TOC in sediments (t)	%Eroded TOC with respect to the stock in soils
P 1997[a]	−0.808 $p = 0.028$	–	–	–	–
Decrease DA[b] 1981–1997	–	–	–	–	0.857 $p = 0.014$
Increase HDF 1981–1997[c]	–	–	–	–	–
Increase MDF 1981–1997[d]	–	–	–	–	–
Increase LDF 1981–1997[e]	–	–	–	–	–
Increase S 1981–1997[f]	–	–	–	–	–
Increase P 1981–1997	–	–	–	−0.808 $p = 0.028$	–
Decrease DA 1956–1997	–	–	–	–	–
Increase HDF 1956–1997	–	–	–	–	–
Increase MDF 1956–1997	–	−0.786 $p = 0.036$	–	–	–
Increase LDF 1997–1956	–	–	–	–	–
Increase S 1997–1956	–	–	–	–	
Increase P 1997–1956	–	–	–	–	
Fragmentation index DA 1981	0.757 $p = 0.049$	–	–	–	

[a] P: pasture.
[b] DA: dry land agriculture.
[c] HDF: high density forest.
[d] MDF: medium density forest.
[e] LDF: low density forest.
[f] S: shrubland.

catchment outlet, while in larger catchments the sediments are more likely to be deposited within the catchment. Furthermore, the negative correlation between slope and eroded C can be explained because subcatchments with a smoother average slope and a high percentage of agricultural area show higher rates of TOC erosion (Tables 1 and 8).

Extrapolating the results at catchment scale, the amount of soil C eroded is estimated at 1760 t in 27 years. This figure, when related to the soil C stock in the first 5 cm of soils with the land use pattern of 1974 (two years before the start of the hydrological correction works), implies that a minimum of 4% of the soil C stock in the first 5 cm has been eroded (0.15% per year). At the catchment scale this means a TOC erosion/total erosion ratio of 0.010 (a 1% of TOC erosion from a total erosion rate of 0.06 t ha^{-1} $year^{-1}$). This result is comparable with the ratio obtained for the Mississipi catchment in a predominantly agricultural landscape and at a larger scale, of 1.5% of TOC erosion from a total erosion rate of 0.07 t ha^{-1} $year^{-1}$ (Smith et al., 2005).

The change of C stock at the catchment level between 1974 and 1997 implied an increase of 36% of soil C in the first 5 cm of soil depth. This means that between 1974 until 1997 and probably until the present (assuming that the land use pattern of 1997 is very similar to the pattern nowadays) the Rogativa catchment has behaved as a C sink within the soil erosion cycle. Of the 4% of the soil C stock mobilized by water erosion, 77% is buried in the sediment wedges behind check-dams. The replacement due to an increase of the vegetation cover through land use changes represents an increase of 36% of the original soil C stock. The installation of check-dams and the land use changes since 1956 (including the reforestation works of 1976) imply a 40% of soil C sequestration with respect to the original C in 1974.

3.5. Relations between eroded SOC and land use change

The significant correlations between land use, land use change and indicators of TOC erosion can be seen in Table 8. These correlations show complex relations, at the subcatchment level it seems that the subcatchments showing a more pronounced reduction of agricultural areas have higher percentages of eroded TOC with respect to the original soils, because of higher concentrations of TOC in the removed sediments from soils under more vegetated surfaces richer in soil C. A positive relation between the fragmentation of the agricultural landscape and the concentration of TOC in sediments is evident. This indicates that sediments removed from a mosaic agricultural landscape, alternating with natural vegetation areas, are richer in C content. This is in agreement with the results of Albergel et al. (2006) and Martinez-Mena et al. (2008) for other Mediterranean areas. Higher percentages of pasture are associated with lower concentration of TOC in sediments. Besides this general tendency to find sediment richer in organic C coming from non-agricultural sources, an increase in the forest in the whole studied period indicates a reduction in the TOC erosion rate (negative correlation between increase MDF (Medium Density Forest) 1997–1956 and eroded TOC, Table 8). Obviously, this is due to a general decrease in total erosion rates in more densely vegetated catchments compared to catchments dominated by agricultural fields.

4. Conclusions

The hydrological control works (afforestation and check-dam construction) in the mid 1970s, together with the progressive abandonment of agricultural activities, have led to the Rogativa catchment behaving as a soil erosion-induced C sink from the 1950's onwards. Soil C was partially removed from the slopes and buried in the sediment wedges created behind check-dams along the river channels. Soil C was also replaced due to an increase of land use types (reforestation, agricultural land abandonment replaced by pasture and shrubland) with higher concentrations of soil C. It is estimated that the sink accounted for approximately 40% of the soil C stock of the first 5 cm of soil in the catchment in 1974, two years before the start of the hydrological control works.

These estimations strongly suggest that the increase in vegetation cover experienced in many Mediterranean catchments, especially in mountain areas after the abandonment of agricultural and grazing activities (e.g. Pyrenees valleys (Beguería et al., 2006; López-Moreno et al., 2006); see examples from Italy, France and Slovenia in the review of Boix-Fayos et al., 2007) may lead to significant increases in soil C sequestration. Together the catchments act as C sinks within the soil erosion cycle at this scale.

However, it remains open what this sink of C due to a recovery of the vegetation and the buried of eroded sediments means in a wider C balance, taking into account an important C output as soil respiration.

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