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Soil crusting impact on soil organic carbon losses by water erosion

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ABSTRACT

The Sahelian region, characterized by erratic, heavy rainfalls and low soil organic carbon (SOC) stocks, is highly vulnerable to land degradation. While water erosion is recognized as being a main mechanism of SOC losses, little research has yet been done to investigate the role which soil surface crusting might have on SOC losses. The main objective of this study was to evaluate the impact of soil surface crusting on SOC losses. This study was conducted in Tougou Catchment (37 km^2), northwest of Burkina Faso, which receives a cumulative mean annual rainfall of 500 mm y^{-1}. The area is characterized by sandy soils with varying types of surface crusts. The four different crust types studied were: structural crusts (STRU), which were found under cultivated soils, which were plowed annually; perennial desiccation crusts (DES), gravel (GRAV) and erosion (ERO) crusts, generally found in the degraded semi-arid savannas. Three micro-scale runoff plot (1×1 m^2) replicates were installed on each of the different types of surface crusts observed in the catchment. Water and sediment samples were collected from the runoff plots after every rainfall event ($n = 10$) of the 2011 rainy season. The sediment samples were analyzed for organic carbon (OCsed), while the water samples were examined for dissolved organic carbon (DOC). The average of organic carbon losses with sediment (OC_Lsed), was 0.37 g C m^{-2} y^{-1} for ERO, 0.36 g C m^{-2} y^{-1} for DES, 0.24 g C m^{-2} y^{-1} for STRU and 0.15 g C m^{-2} y^{-1} for GRAV. DOC accounted for a minute contribution to SOC losses i.e. less than 0.05%. STRU with 10.42 mg C l^{-1} showed the highest DOC content, followed by GRAV (6.13 mg C l^{-1}), DES (5.06 mg C l^{-1}) and ERO (4.92 mg C l^{-1}). The OC enrichment ratio (ER) of sediments to that of the 0–0.1 m bulk soil was less than one for DES, GRAV and ERO (0.39, 0.69 and 0.75, respectively) and reached 1.14 for STRU. This pointed to a greater SOC protection from erosion by the perennial crusts of the degraded savannas (DES, GRAV and ERO), as compared to crusts of cultivated fields. Thick, sand-enriched crusts, DES and GRAV, seemed to provide the greatest OC protection. This study pointed out a significant relationship between soils crusting on SOC erosion. It showed that the formation of loose and sandy crusts provides greater SOC protection from water erosion, which in turn may improve SOC stabilization and associated soil functions, such as soil fertility, water-holding capacity and sequestration of atmospheric carbon.

1. Introduction

Soil organic carbon (SOC) is a vital component of natural ecosystems. It maintains a key role in the regulation of food and biomass production through its positive influence on nutrient availability, water retention and biodiversity (Bationo et al., 2007; Jacinthe et al., 2004; Lal, 2004). SOC also reduces the risks for soil compaction, soil surface crusting and soil erosion (Hien et al., 1996). An estimated 60 Gt C are exchanged annually between land surface and the atmosphere (Folger, 2009). Because large amounts of SOC are stored in world soils, approximately 2500 Gt C to a depth of 2 m (Robert, 2002), soil degradation can accelerate SOC turnover and increase the strength of CO_2 emissions from terrestrial ecosystems (Lal, 2003). SOC erosion is one of the principal mechanisms of land degradation (Bationo et al., 2007; Lal, 2003), yet little is known about its impact on the soil C cycle.

Soil water erosion is the process by which soil material (either organic or inorganic) is removed from its initial place, by a combined action of raindrop energy and runoff. Water erosion affects SOC by (1) complete transport and removal of entire surface soil aggregates (Goebel et al., 2005); (2) preferential removal of SOC, resulting from the break-down of soil aggregate, by either raindrop impacts or runoff (sheet-erosion) (Lal, 2003).

The intrinsic quality of soils determines their ability to be affected by water erosion, with clayey and SOC rich-soils exhibiting more

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stable soil aggregates than sandy soils and soils that have a low SOC content. The semi-arid regions of the world are characterized by a low SOC content, being naturally higher in their sand content. These regions are then more vulnerable to SOC erosion. Such degradation can be exacerbated by rapid turnover rates of organic material due to high soil temperatures and faunal activity, as well as land misuses (Batjes, 2001; Sarah, 2006; Sinoga et al., 2012).

One of the few studies available in the region was conducted by Roose (1980) in the Ivory Coast (mean annual precipitation, MAP, of 2100 mm). This study used 22.5 m^2 Wischmeier plot replicates under maize cultivation. SOC losses were found to be as high as 180 g C m^2 y^{-1}. These SOC losses were much higher than the rate measured in Burkina Faso by the same author (Roose, 1978) (20 g C m^2 y^{-1}), under similar plot and land use conditions. The only striking difference is the much lower mean annual precipitation MAP (800 mm) in the latter study. To our knowledge, two studies on SOC erosion are available in semi-arid conditions of Africa. The first, by Moyo (1998), conducted in Zimbabwe, receiving an annual amount of 500 mm of rain, reported SOC losses close to 20 g C m^2 y^{-1}. The second one, conducted in Ethiopia (MAP = 540 mm), showed SOC losses between 1.4 g C m^2 y^{-1} and 26.3 g C m^2 y^{-1} (Girmay et al., 2009). The highest value in the latter study results is found under maize and the lowest under grassland.

Most of sub-Saharan Africa soils show impermeable soil surface crusts (Graef and Stahr, 2000), which create a physical barrier to seedling and plant root development. In the event of the pores in the crusts becoming blocked, their water infiltration capacity is greatly impaired, thus potentiating runoff and soil erosion. In their evaluation of 10 sites (from Niger, Burkina Faso, Ivory Cost, Togo, and Cameroon), Casenave and Valentin (1992) identified seven different crust types. The most common crusts are structural crust (STRU), desiccation crusts (DES), erosion crusts (ERO) and gravel crusts (GRAV). The desiccation crust (DES) is characterized by the presence of a single sandy micro-horizon outcrop on the soil surface. The structural crust (STRU) is composed of two micro-horizons: a sandy layer overlying a thin film of soil plasma. Compared to STRU crusts, gravel crusts (GRAV) display an additional gravel micro-horizon on the surface. Finally, erosion crusts (ERO) consist of a thin, clayey micro-horizon. There is a tendency for ERO crusts to develop in clayey soil horizons, DES and STRU to develop under sandy soil conditions and for GRAV crusts to form under the coarsest soil textures (Casenave and Valentin, 1989). Several studies (de Rouw and Rajot, 2004; Graef and Stahr, 2000; Karambiri et al., 2003; Malam-Issa et al., 2011) in the Sahel supplied information on impacts of soil crusting on infiltration and soil erosion, yet, little is known about the impacts of soil crusting on SOC losses.

In this study conducted in northwest of Burkina Faso, being characteristic of sandy soils and a dry climate, receiving the cumulative annual rainfall amount of 500 mm y^{-1}, our main objective was to quantify the differences in SOC losses by water erosion for different soil surface crusts.

2. Materials and methods

2.1. Study area

The study was conducted in Tougou catchment, Lat. 13°11′ N; Long. 2°64′ E, located in the upper reaches of the Nakanbe basin, northwest of Burkina Faso (Fig. 1). Climate is semi-arid with mean annual precipitation of 500 mm and temperature of 28 °C. The dry season extends from October to May, and the wet season stretches from June to September with peak rainfalls generally recorded in July/August.

The main soil type in the region developed from clayey sandstone and migmatites, is classified as Ferric lixisol (WRB). The soils are largely depleted of organic matter (Table 1) and are thus very prone to soil crusting and soil erosion. The average slope gradient ranges between 0.5 and 1.5% in the bottomlands, 1–2% at footslope, and 2–4% at midslope position. The traditional crops in the region are millet (*Panicum miliaceum*), groundnuts (*Arachis hypogaea*), sorghum (*Sorghum bicolor*) and cowpea (*Vigna unguiculata*), with the growth period stretching from 80 to 110 days.

2.2. Experimental design

The rates of soil organic carbon erosion by water were evaluated at runoff micro-plot scale. The underlying hypothesis is that dominant erosion processes that govern under indurate soil surfaces in the Sahel region are associated with sheet and splash erosion. Micro-plots were chosen because OC outputs from soils, due to water erosion, are intuitively associated with “point” detachment and transport processes where splash predominates. OC erosion was quantified using 1 × 1 m^2 micro-plots when splash and little rain-impacted flow were the two main erosion processes (Kinnell, 2001). Three micro-plot replicates were installed on each crust type: structural (STRU), erosion (ERO), gravel (GRAV) and desiccation (DES), totaling twelve micro-plots. These surface crusts were identified visually using the method described by Casenave and Valentin (1989), based on the micro-horizon characterization.

The micro-plots were composed of steel sheets inserted into the soil to a depth of 0.1 m and were used as plot boundaries. Runoff and sediments were collected at the downslope end of each micro-plot, using a metallic gutter connected to a 50 liter tank by a PVC pipe.

2.3. Evaluation of runoff, soil and soil organic carbon erosion

Field measurements were carried out from the 20th June 2011 to the 5th October 2011. It was assumed that measurements were made under steady-state soil loss conditions, since no significant soil cracks or features of rill erosion were observed on the surface of any of the plots. After each rainstorm, the runoff volume (R) was measured in the tank. Aliquot samples of 1000 ml were taken to determine the DOC content. The OC in the aliquots was preserved from biological decomposition by adding 2 drops of a 50 mg l^{-1} solution of aluminum sulfate to every liter. A 50 ml sub-sample was filtered with a 0.45 μm Whatman filter paper prior to the DOC analysis. The samples were analyzed for DOC content (DOC_C) with a Multi Analyzing N/C 2100 S, at maximally 24 h after field sampling was conducted.

The sediments from the 1000 ml aliquot and those collected from the micro-plot gutters were oven-dried at 50 °C and weighed, to determine the average sediment concentration (SC). The dried sediment samples were further analyzed for organic carbon content (OC_Csed).

The dichromate oxidation procedure was utilized to determine the organic carbon content in sediments. The dried samples were sieved, using a 2 mm sieve to remove coarse materials and were further crushed with a mortar and sieved again at 0.1 mm. One gram of the resulting dry material was placed into a 100 ml flask and mixed with 15 ml of 85% H_2SO_4. The mixture was shaken for a period of 10 min before adding 10 ml of an 80% $K_2Cr_2O_7$ solution. Thereafter, the mixture was stored in an oven at 120 °C for 90 min. After the oven, the samples were allowed to cool to room temperature and distilled water was then added to the mixture. A 25 ml volume of the liquid solution was mixed with 1 ml of 85% H_3PO_4 solution and titrated with 0.25 mol l^{-1} of $FeSO_4$. The OC content in the sediment was then expressed in gram of carbon per kilogram of sediment (g C kg^{-1}).

Both DOC_C and OC_Csed were converted into losses following Eqs. (1) and (2).

$$DOC_L = DOC_C \times R \tag{1}$$

$$OC_L\mathrm{sed} = OC_C\mathrm{sed} \times SC \times R \tag{2}$$

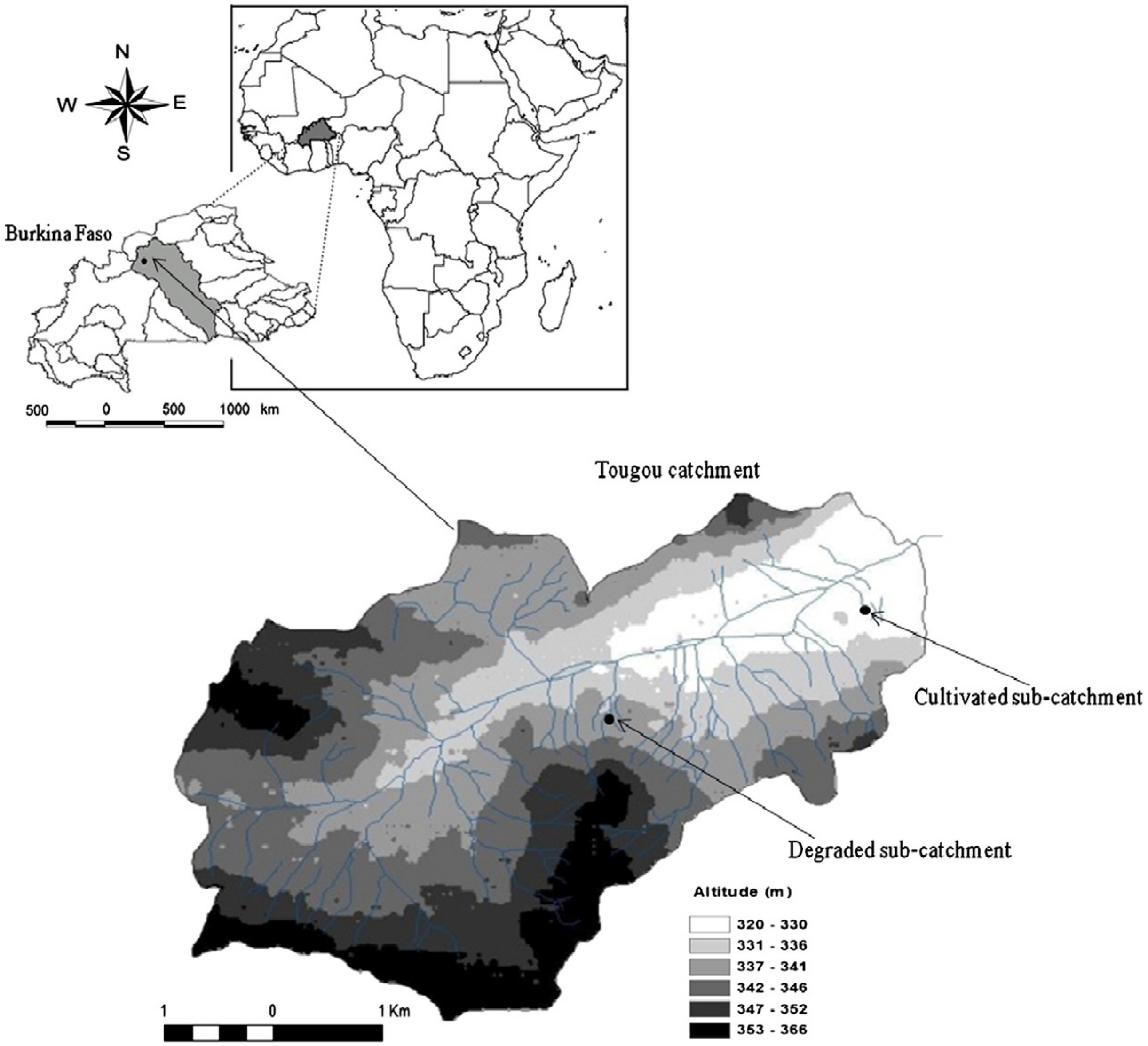

Fig. 1. Localization of the study site in Northwest Burkina Faso with the two sub-catchments studied.

where DOC_L is dissolved organic carbon losses in mg C m^{-2}, OC_Lsed is the loss of organic carbon in sediments in g C m^{-2}. SC is the sediment content in g l^{-1} and R, the runoff in l m^{-2}.

2.4. Evaluation of soil organic carbon stocks

Soil samples from the 0–0.1 m soil layer were taken in the vicinity of each micro-plot to evaluate the soil organic carbon content (OC_Csoil). The same procedure used for sediments i.e. dichromate oxidation, was used for the bulk soil to determine the organic carbon content.

Undisturbed soil samples were also collected to determine soil bulk density. The method consisted of inserting a metal 100 cm^3 cylindrical core in the soil. Triplicate bulk density samples were taken at each micro-plot. The samples were oven-dried at 105 °C for 24 h to determine their dry weight. The soil bulk density was calculated as follows:

$$\rho_b = \frac{M_S}{V_t} \quad (3)$$

Table 1
General properties of topsoil on 0–0.1 m layer on different surface crusts in the site study. OC_Csoil: soil organic carbon content; OC_Ssoil: soil organic carbon stock; ρ: bulk density; Clay: 0–2 μm; Silt: 2–50 μm; Sand: 50–2000 μm; Coarse: 2000–5000 μm.

Land use	Crust type	Texture				ρ[a]	OC_Csoil[a]	OC_Ssoil[a]
		Coarse	Sand	Silt	Clay			
		%				g cm^{-3}	g C kg^{-1}	g C m^{-2}
Agriculture	STRU	3	70	19	9	1.70	3.00	510.5
Savanna	DES	0	81	13	6	1.66	2.80	465.5
Savanna	GRAV	15	38	7	40	1.90	4.13	785.9
Savanna	ERO	0	21	25	54	1.60	7.30	1168.1

[a] Significant at $p < 0.001$.

where ρ_b is the soil bulk density in g cm^{-3}; M_S is the mass of oven dry soil in g; and V_t is the core volume in cm^{-3}.

Subsequently, soil carbon stock (expressed in g C m^{-2}) for the top 0.1 m of the soil was calculated as the product of ρ_b, OC_Csoil and thickness of considered soil layer, following Eq. (4).

$$OC_S\text{soil} = OC_C\text{soil} \times \rho_b \times x_1\left(1-\left(\frac{x_2}{100}\right)\right) \times b \tag{4}$$

where OC_Ssoil is the OC stock (g C m^{-2}) of the 0–0.1 m soil layer; OC_Csoil is the OC content in the ≤2 mm soil material (g C kg^{-1}); x_1 is the thickness of the soil layer (m); x_2 is the proportion of fragments of >2 mm in percent; and b is a constant equal to 0.001.

The soil texture on the 0–0.1 m soil samples was also assessed. The method consist of silt, clay and sand fraction determination, after having sieved the samples at 2 mm and having removed all organic matter with H_2O_2 and chemically dispersed with 5% of sodium hexametaphosphate.

2.5. Enrichment of sediment in OC

The enrichment of sediments in OC was estimated following Eq. (5) as a means to evaluate the process of OC destabilization from soils by water erosion.

$$\text{ER} = \frac{OC_C\text{sed}}{OC_C\text{soil}} \tag{5}$$

where ER is the OC enrichment ratio, OC_Csoil is the OC content in the bulk soil and OC_Csed is the OC content in sediments. A ratio above 1 would reflect a preferential removal of OC by overland flow.

2.6. General statistics

The descriptive statistics (minimum; maximum; average; median; variance) were used to describe the water erosion products (R, SC, SL), soil organic carbon, enrichment ratio and organic carbon losses (OCsed and DOC). Statistical analyses were carried out, with SPSS 18, to test between the variables. The Pearson test was used to estimate the correlation matrix between soil characteristics, soil water erosion and OC losses. A Principal Component Analysis (PCA) was constructed using the soil's physical characteristics (texture) and types of crust as active variables and R, SC, SL, OC_Csed, OC_Lsed, DOC_C and DOC_L as supplementary variables. A one-way analysis of variance (ANOVA) was also carried out to test the correlative significance between factors and variables. Significant differences were marked at p level < 0.05 or 0.001.

3. Result

3.1. Rainfall characteristics of the study period

Twenty-six rainfall events occurred during the 2011 rainy season, most of them happening, between July and August. The overall cumulative value for the season's rainfall amounted to 460 mm. The minimum rain event amount was 1 mm and the maximum was 80 mm. The mean rainfall event intensity was between 5.0 mm h^{-1} and 56.5 mm h^{-1} and the median rainfall intensity was at 17.5 mm h^{-1}. The strongest event with a cumulative rainfall of 46 mm occurred on the 12th of August. Fifty eight percent of the storm events produced runoff and erosion.

3.2. Soil characteristics, soil crusting and soil organic carbon stocks

Some selected physical characteristics of the 0 to 0.1 m bulk soil found at each type of crust are presented in Table 1. The proportion of clay particles (Clay) in the soil was the highest for ERO (Clay = 54%), followed by GRAV (40%), whereas STRU and DES had clay contents of only 9% and 6%, respectively (Table 1). Soil under GRAV exhibited a higher content of coarse elements (Coarse = 15%) in comparison to STRU (Coarse = 3%) and ERO and DES, for which no gravels were found. Soils below DES and STRU crusts were rich in sand (Sand = 81% and 70%, respectively) while ERO crust soils exhibited the highest silt content among crusts (Silt = 25%). Organic carbon stock for the 0–0.1 soil layer (OC_Ssoil) greatly differed among the crust treatments (Table 1). The highest OC_Ssoil was found in ERO (OC_Ssoil = 1168.1 g C m^{-2}), followed by GRAV (785.9 g C m^{-2}), STRU (510.5 g C m^{-2}) and DES (465.5 g C m^{-2}) (Table 1) and these differences were statistically significant, at P < 0.001 level.

3.3. Soil crusting impact on runoff and sediment losses

The mean annual runoff amount (R) from the micro-plots, measured over one rainy season, was 15.7 l m^{-2} y^{-1}. Fig. 2 displays the general statistics of R, SC and SL for the different crust types. R ranged from 11.0 l m^{-2} y^{-1} on STRU to 21.1 l m^{-2} y^{-1} on GRAV. DES and ERO crusts showed an R value of 13.0 and 17.7 l m^{-2} y^{-1}, respectively

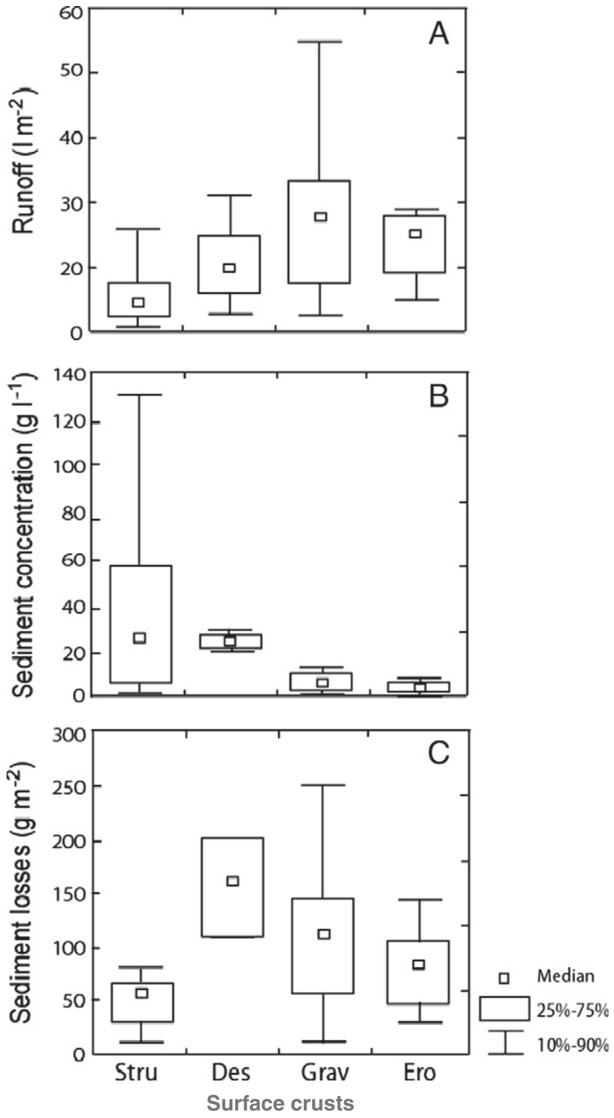

Fig. 2. Box-plots of erosion products: runoff, sediment concentration and sediment losses on micro-plots replicated and installed on four crust types.

(Fig. 2A). These corresponded to significant differences at $P < 0.05$ level. There was a general correlation between R and rainfall amount ($p < 0.01$, Table 2). The cumulative R displayed a similar behavior on DES, GRAV and ERO crusts, i.e. a constant increase towards the rainy season at however a sharper rate from early to mid August. This contrasted with cumulative R curve for STRU that increased at a relatively constant pace through the season.

The average of sediment concentration (SC) in runoff was 56.8 g l^{-1} for STRU and sharply decreased to 18.2 g l^{-1} for DES, 6.0 g l^{-1} for GRAV and 4.7 g l^{-1} for ERO (Fig. 2B). These differences were significant at $p < 0.05$ level. A maximum of 287.9 g l^{-1} occurred on September 13 on STRU. While SC was the highest during heavy rainfall, it exhibited a negative Pearson r coefficient with soil clay content and a positive one with soil sand content. These results suggest that the higher the soils sand content, the higher is the SC in runoff.

Soil crusting significantly impacted sediment losses ($P < 0.001$); the minimum rate of sediment losses was 11.8 g m^{-2}y^{-1} and was found on STRU, while the maximum losses occurred on DES (SL = 470.5 g m^{-2}y^{-1}, Fig. 2C). This result shows that soil rich in sand or coarse, loses most of its soil by erosion.

3.4. Soil crusting impact on soil organic carbon losses

3.4.1. Dissolved organic carbon

Soil crusting, had a significant impact on both dissolved organic carbon content (DOC$_C$) and losses (DOC$_L$). The differences observed between the different crust types were significant at $p < 0.05$. For example, the average DOC$_C$ in runoff decreased from 16.9 mg l^{-1} at STRU, 6.1 mg l^{-1}at GRAV, 5.1 mg l^{-1} at DES to 4.9 mg l^{-1} on ERO (Fig. 3A). The average DOC$_L$ was the highest on GRAV (129.6 mg C m^{-2} y^{-1}), followed by ERO (81.4 mg C m^{-2} y^{-1}), DES (68.7 mg C m^{-2} y^{-1}) and STRU (34.6 mg C m^{-2} y^{-1}) (Fig. 3B), which corresponded to 16.5%, 7%, 14.8% and 6.8% of OC stocks on GRAV, ERO, DES and STRU, respectively.

The variations of DOC$_L$ followed a similar trend to that of OC$_L$sed, meaning greater losses on STRU at the onset of the rainy season and ultimately the lowest losses on STRU among all crust types towards the end of the rainy season. Surprisingly, DOC$_C$ did not significantly correlate with some selected soil physical properties, but rather, DOC$_L$ significantly correlated to the soil clay content and rainfall amount (P) (Table 2).

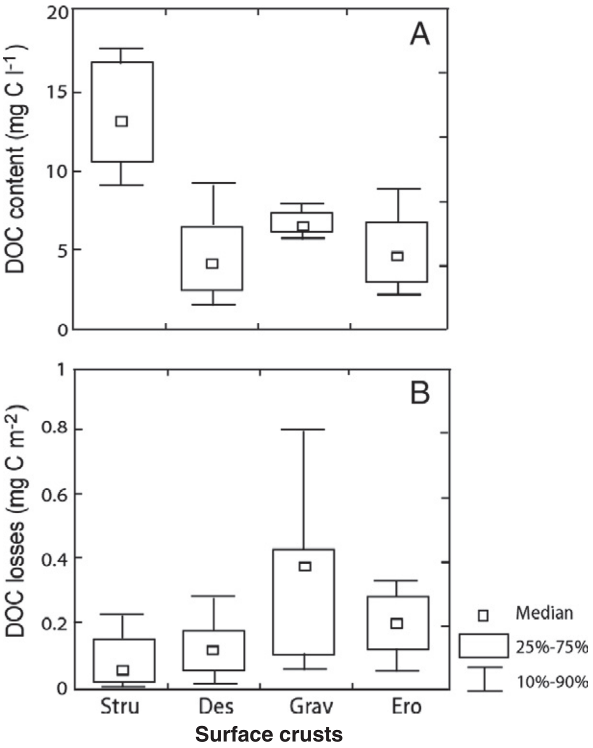

Fig. 3. Box-plots for dissolved organic carbon content (DOCc) and dissolved organic carbon losses (DOC$_L$) for 11 erosive events on four types of surface crusts found in the study site.

3.4.2. Organic carbon in sediments

Fig. 4 displays the general statistics of OC$_C$sed, OC$_L$sed and OC enrichment ratio for the different crust types. Soil crusting had a significant ($P < 0.001$) impact on organic carbon content in sediments (OC$_C$sed). The average OC$_C$sed, computed from all micro-plot sediments, was 3.15 g C kg^{-1}, with the highest value (5.5 g C kg^{-1}) observed on ERO, followed by STRU (3.6 g C kg^{-1}) and DES (1.9 g C kg^{-1}), the lowest value being found for GRAV (1.6 g C kg^{-1}) (Fig. 4A). Table 2, showing correlation coefficients between OC$_C$sed and the selected soil physical properties, indicated an increase in OC$_C$sed with increasing soil silt content, but decreasing sand content.

Table 2
Correlation matrix between soil texture (Sand, Silt, and Clay), bulk density (ρ), rainfall amount (P) and soil water erosion product and soil organic carbon losses.

	P	Sand	Silt	Clay	ρ
R	0.678**	−0.178	−0.033	0.258	0.173
SC	−0.233	0.126	−0.076	−0.328*	−0.063
SL	0.231	0.494*	−0.157	−0.266	−0.044
OC$_C$sed	−0.114	−0.506*	0.727**	0.368*	−0.559*
OC$_L$sed	0.051	0.077	0.325*	0.033	−0.374*
ER	−0.144	0.051	0.206	−0.355*	−0.370*
DOCc	−0.253	0.010	−0.094	−0.276	0.006
DOC$_L$	0.486**	−0.171	−0.184	0.349*	0.373*

* Significant correlation at 0.05.
** Significant correlation at 0.01.

Unlike the STRU, organic carbon content in soils from DES, GRAV and ERO was higher than organic carbon content in sediments from these surface crusts. The average of OC enrichment ratios (ER) from GRAV, DES, ERO was below one (0.39; 0.69 and 0.75 respectively), but reached 1.23 for STRU (Fig. 4C). The differences between surface crusts were statistically significant at $p < 0.001$. ER was negatively correlated with soil clay, but decreased as the clay content in the soil increased. In general, the ER followed the same evolution over time for all surface crusts, with the maximum found on 12 August and 25 July. ER was not correlated with rainfall amount.

The resulting average organic carbon losses by water erosion at micro-plot level were less than 1 g C m^{-2}y^{-1}, regardless of type of crust (Fig. 4B). The differences in (OC$_L$sed) between types of crusts were not statistically significant. OC$_L$sed were the highest for STRU, compared to the other crust types, at the onset of the rainy season, thereafter, OC$_L$sed on STRU only increased slightly and ranked last among the crust types at the end of the rainy season, far below ERO and DES, both with about 4 g C m^{-2} y^{-1}. Ultimately, OC$_L$sed represented a limited proportion of the 0–0.1 m OC stocks in soil, which ranged from between 0.04% for STRU, 0.09% for DES to 0.03% for GRAV and ERO.

3.5. Controlling factors of SOC erosion

A multivariate analysis was performed, using a Principal Component Analysis (PCA), to investigate the link between OC erosion and selected soil and environmental characteristics (Fig. 5). The two first axes of PCA between the soil's physical characteristics and the types of crust, and R,

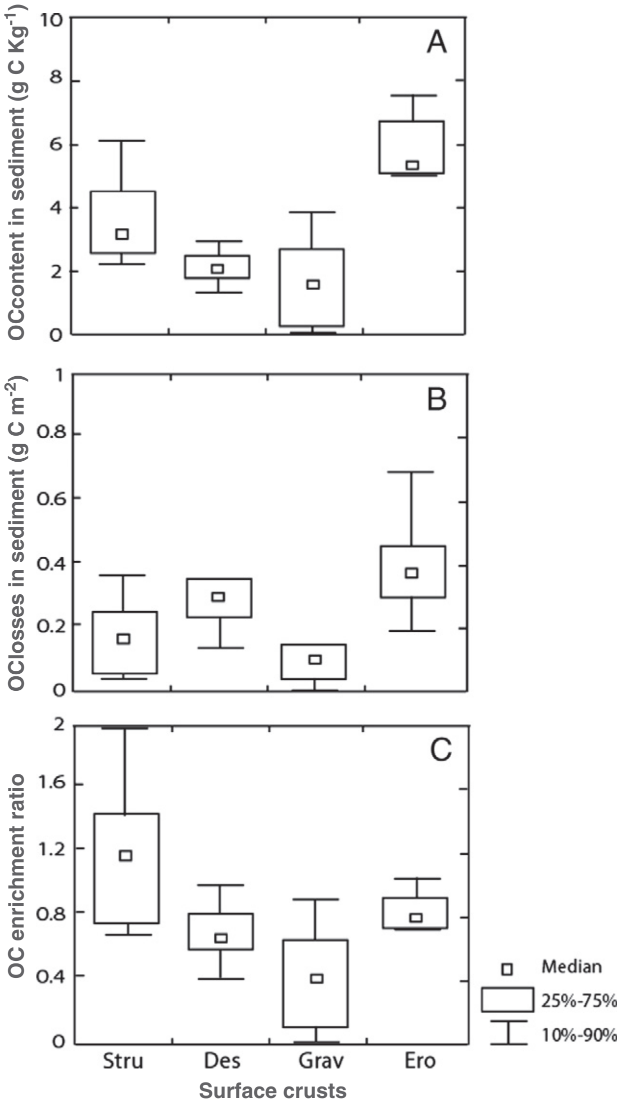

Fig. 4. Box-plots for organic carbon content in sediment (OC_Csed), organic carbon losses in sediment (OC_Lsed) and organic carbon enrichment ratio for 11 erosive events on four types of surface crusts found in the study site.

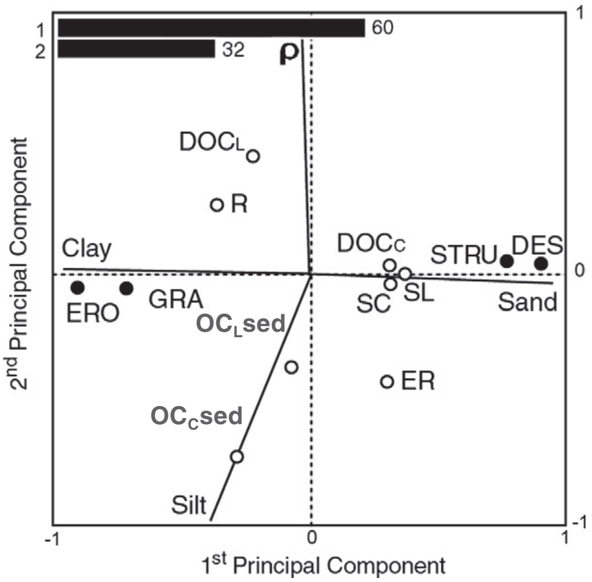

Fig. 5. Principal Component Analysis (PCA) for all variables.

SC, SL, OC_Csed, OC_Lsed, DOC_C and DOC_L, explained 93% of the entire data variance (Fig. 5). The first axis accounted for 60% of the entire data variance and the second axis accounted for 33%. Because clay and silt had negative coordinates on Axis 1 and sand had a positive coordinate, this axis can be interpreted as an axis of increasing soil particle size. Crust type was highly correlated with Axis 1. STRU and DES crusts showed a positive coordinate on Axis 1, confirming a sand enrichment of soils below these crusts, a result initially presented in Table 1. Conversely, GRAV and ERO crusts had a negative coordinate on Axis 1 as a result of higher soil clay content. The second PCA axis, explaining 32.6% of the data variance, was associated with soil bulk density and to a lesser extent with silt content. The denser soils had positive coordinate on Axis 2. Interestingly, soil silt content correlated with both Axis 1 and Axis 2, proportion of silt increased as sand content and bulk density decreased.

SC, SL and DOC_C exhibited positive coordinates on Axis 1, it can therefore be concluded that sediment detachment and transport as well as concentration of DOC in R increased with soil sand content. Moreover, it is apparent from this PCA that OC content and losses in sediments increased with soil silt content. ER (the enrichment of sediments in OC) increased as the soil clay content decreased. Finally, runoff only correlated little with Axis 1 and Axis 2.

4. Discussion

4.1. Soil crusting impact on soil erosion

The effect of soil crusting on runoff (R) was not significant at $P < 0.05$ level. This was a surprising result, in disagreement with that of Casenave and Valentin (1992) who concluded that soil surface crusting is a key controlling factor of water infiltration and runoff generation in West Africa. The lack of a significant effect of surface crusting on R is the most likely due to other features that may have masked the effect of crusting on water infiltration. For example, soil texture may be a feature that significantly impacted on runoff, as suggested by Casenave (1991) and Casenave and Valentin (1992). Other parameters such as vegetation cover and faunal activities may also play important roles in water infiltration. Therefore, these results suggest that the relationship between soil crusting and runoff generation could be more complex than previously thought.

The impact of soil texture on the crust's underlying soil material is partly confirmed by our PCA analysis, showing lower runoff rates from sandy soils than from clayey ones. This is in agreement with the work of Ribolzi et al. (2006), who reported lower water infiltration on clayey ERO crusts. The low level of R on STRU, compared to DES in the present study, can be attributed to the localization of STRU in agricultural soil, where soil tillage destroys surface crusts and enhances soil porosity. The low infiltration rate of GRAV crust is likely to be a result of the formation of micro-horizons, where coarse elements are cemented into crusts (Casenave, 1991).

Irrespective of rainfall characteristics, the variation of runoff on DES, GRAV and ERO crusts followed similar behavior i.e. an increase from the beginning and towards the end of the event. However, this trend differed for STRU, with high initial and final runoff rates during the rainy season. STRU had the initial highest rate among the crusts. This was probably due to the existence of bare soil conditions, which allowed the reorganization of soil particles at the soil surface, increasing the soil's impermeability. This impermeable crust, which initially developed on STRU (localized in agricultural soil), is further disrupted by tillage operations, explaining the greater soil infiltration observed during most of the rainy season.

4.2. Soil crusting impact on soil organic carbon losses

The annual losses of organic carbon (OC_Lsed) from the soils under study were less than $1\ g\ C\ m^{-2}\ y^{-1}$. This was in agreement with other studies (Martínez-Mena et al., 2002, 2012; Quinton et al., 2006) performed in areas of similarly low mean annual precipitations (MAP < 650 mm) (Table 3). However, OC_Lsed in the present study was much lower than the values generally reported in the literature for semi-arid regions (Boix-Fayos et al., 2009; Girmay et al., 2009; Morsli et al., 2006). For instance, Morsli et al. (2006) in North Africa with a MAP of 470, estimated OC_Lsed to be between 0.9 and $4.8\ g\ C\ m^{-2}\ y^{-1}$, with a mean of $2.8\ g\ C\ m^{-2}\ y^{-1}$. Moyo (1998) in Eastern Zimbabwe (MAP = 500 mm) found OC_Lsed losses to be as much as $20\ g\ C\ m^{-2}\ y^{-1}$. Only Rodriguez Rodriguez et al. (2004) and Martínez-Mena et al. (2002, 2012) in Spain, with 300 < MAP < 730 mm, found values of about $1\ g\ C\ m^{-2}\ y^{-1}$ (Table 3). Finally, higher rates of OC losses by erosion were previously found in Burkina Faso by Roose (1978), with $20.0\ g\ C\ m^{-2}\ y^{-1}$ of lost organic carbon (Table 3). Our results conflicted with those found by Roose (1978). One possible explanation for the low rate of OC losses from these crusts could be the presence of thick sandy or gravel layer, which is depleted in OC, but provides physical protection to OC.

With the exception of Boix-Fayos et al. (2009) and Rodriguez Rodriguez et al. (2004), all studies from semi-arid regions found an enrichment of sediment in organic carbon compared to bulk soil, as expressed by ER of over unity (Table 3). These points to a tendency by soil water erosion to preferentially remove OC from bulk soil. The average enrichment ratio for the crusts investigated in the study was significantly lower one (0.39 < ER < 0.75). The average enrichment of sediments in organic carbon was found in STRU crust to be 1.23, which was consistent with previous findings (Bertol et al., 2007; Girmay et al., 2009; Mchunu and Chaplot, 2012; Morsli et al., 2006; Moyo, 1998). This was previously explained by the light nature of organic matter that makes it easily transported by runoff (Avnimelech and McHenry, 1984; Jin et al., 2009). The low enrichment ratio of sediments from DES, GRAV and ERO crusts could be explained by the physical protection that surface crust confer to the soil layer underneath, as suggested by Fig. 6. Indeed, the accumulation of coarse particles observed on the soil surface at GRAV may have provided protection to the underlying soil OC, both from detachment by raindrops, as the coarse particles buffer the impact of raindrops, and from transport as they act as a protective coat, thus preventing transport (Fig. 6). The effect of coarse particles on SOC protection may, to some extent, be compared to that produced by vegetation. A similar level of SOC protection was found on DES crusts, characterized by the accumulation of large amounts of sand, and on GRAV, showing gravel accumulation (Fig. 6). The fact that DES crusts experienced a greater OC enrichment in sediments than GRAV crusts might be explained by the greater SOC protection provided by gravels, as compared to sand particles. Moreover, as suggested by the work of Tisdall and Oades (1982) on aggregate stability, the clayey texture at ERO is likely to generate relatively stable aggregates with a high organic matter content and these aggregates are more likely to be detached and transported. This is partly confirmed by our own results, where ER was significantly correlated with soil clay content, which was in concordance with the findings of Avnimelech and McHenry (1984) and Jin et al. (2009). Finally, ER increases with sand content in soil, which is in accordance with the finding of Feller et al. (1991) who suggested that organic carbon content in soil decreases with increasing sand proportion in the soil.

Our results pointed out the significant impact of soil crusting on the dissolved organic carbon losses by water erosion. The average DOC losses ($78.6\ mg\ C\ m^{-2}\ y^{-1}$) was a higher value than found by other authors under relatively similar conditions, $0.29\ mg\ C\ m^{-2}\ y^{-1}$ for Martínez-Mena et al. (2008); $0.0049\ mg\ C\ m^{-2}\ y^{-1}$ for Rodriguez Rodriguez et al. (2004) and $5.05\ mg\ C\ m^{-2}\ y^{-1}$ for Diallo et al. (2004), respectively. DOC presents the significant difference between surface crusts $34.6\ mg\ C\ m^{-2}\ y^{-1}$ from STRU; $68.7\ mg\ C\ m^{-2}\ y^{-1}$ from DES; $129.6\ mg\ C\ m^{-2}\ y^{-1}$ from GRAV and $81.4\ mg\ C\ m^{-2}\ y^{-1}$ from ERO. The highest value measured on GRAV is probably due to low flow velocity, resulting from the high gravel concentration on the surface, thus increasing the time of runoff-soil contact and SOC dissolution. This issue on the losses of DOC from soil needs further consideration.

5. Conclusion

Soil organic carbon (SOC) in poor semi-arid and arid soils is recognized to be the only support of soil fertility. The existence of scarce and heavy rainstorms poses a threat to sustainability of soil resources in these regions. While numerous studies have investigated soil water erosion, much remains to be learned about the dominant mechanisms of SOC losses in the various world eco-regions.

This study conducted under semi-arid conditions, aimed specifically at investigating the rate of soil OC losses under natural conditions and over an entire rainy season, as well as the impact of soil surface crusting, which is dominant under such environments.

Four crust types, predominantly found in cultivated soils and observed in the degraded tropical savannas, were investigated in this study, namely, STRU (structural crusts), DES (desiccation crusts), GRAV (gravel crusts) and ERO (erosion crusts).

Table 3

Soil organic carbon erosion data established under different climate conditions from different countries; MAP, mean annual precipitation; MAT, mean annual temperature; Z, mean altitude above sea level; n, number of sample; OC_Csed, organic carbon content in sediment, OC_Lsed, organic carbon losses in sediment; ER, enrichment ratio.

Author	Country	n	MAP	MAT	Z	OC_Csed			OC_Lsed			ER
			mm	°C	m	$g\ C\ kg^{-1}$			$g\ C\ m^{-2}y^{-1}$			
						Mean	Min	Max	Mean	Min	Max	
Boix-Fayos et al. (2009)	Spain	7	583	13	1200	9.6	0.7	35.2	6.0	0.4	19.9	0.6
Girmay et al. (2009)	Ethiopia	4	540	27	1500	29.0	21.0	37.3	9.9	1.4	26.3	1.6
Juarez et al. (2011)	South Africa	5	684	17	1385	53.9	50.0	61.1	8.4	3.7	13.0	1.9
Martínez-Mena et al. (2002)	Spain	2	300	17	800				0.3	0.1	0.5	
Martínez-Mena et al. (2012)	Spain	2	300	17	800	44.2	31.0	57.3				2.5
Martínez-Mena et al. (2008)	Spain	3	300	17	800	35.3	25.5	49.4	3.4	1.8	5.1	2.2
Mchunu et al. (2011)	South Africa	2	684	13	29	75.6	65.1	86.0	12.0	7.7	16.2	5.9
Mchunu and Chaplot (2012)	South Africa	3	684	13	1385	0.8	0.5	1.2	4.2	1.9	7.0	1.8
Morsli et al. (2006)	Algeria	14	470	17	585	19.6	9.6	35.7	2.8	0.9	4.8	1.9
Moyo (1998)	Zimbabwe	1	500	26	1479	9.7	9.7	9.7	20.0	20.0	20.0	1.9
Quinton et al. (2006)	United Kingdom	10	621	9	85	39.5	38.0	41.0	0.6	0.6	0.6	3.6
Rodriguez Rodriguez et al. (2004)	Spain	1	730	16	1000	116.0	116.0	116.0	0.9	0.9	0.9	0.8
Roose (1978)	Burkina Faso	1	800	29	400	27.4	27.4	27.4	20.0	20.0	20.0	6.3
Cogle et al. (2002)	India	9	784	27	516	10.7	10.7	10.8	9.0	7.4	11.8	1.3

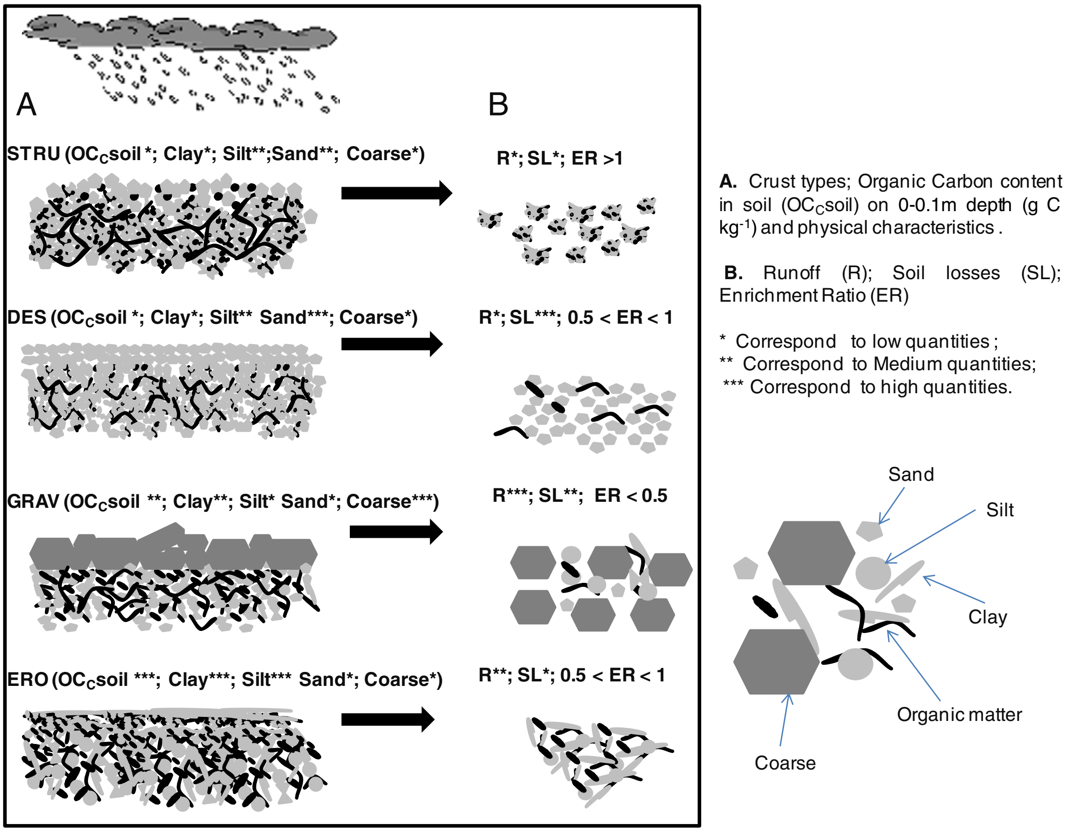

Fig. 6. Process of OC losses by water erosion on different surface crusts. A. Crust types; organic carbon content in soil (OC_csoil) on 0–0.1 m depth (g C kg^{-1}) and physical characteristics. B. Runoff (R); Soil losses (SL); Enrichment Ration (ER).

The main conclusion was that surface crusting has a significant impact on the loss of soil organic carbon but does not show any effect on runoff.

These surface crusts particularly affect soil organic carbon losses of organic carbon in sediment (OCsed). The DOC lost by water erosion accounted for less than 0.05% of total soil organic carbon losses.

Perennial crusts (DES, GRAV and ERO) yielded protection to SOC losses by water erosion, as coarse materials on the land surface can buffer the impact of raindrops and thereby protect the underlying soil layer from erosion. Furthermore, the clayey texture generates a stable aggregate with high organic matter content. These aggregates are more likely to be detached without disaggregation and transported through the micro-plot. From these results, the surface crust can be considered in the modeling of soil organic carbon losses. Clayey and sandy soils control the ER of sediments, therefore should be considered according to their roles in soil infiltration. In conclusion, clayey soils are likely to experience a low ER, but as the sandy content of the soil increases, it favors the formation of crusts and increases the enrichment of organic carbon in sediments.

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