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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).

$$DOC_L = DOC_C \times R \quad (1)$$

$$OC_L\text{sed} = OC_C\text{sed} \times SC \times R \quad (2)$$