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Effect of land degradation on carbon and nitrogen pools in two soil types of a semi-arid landscape in West Africa

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ABSTRACT

To determine the resilience of soil organic C and N pools during land degradation processes in a semi-arid landscape of West Africa, we compared the magnitude of soil organic C and N differences in bulk soil and aggregate fractions between contrasting types of land cover (degraded land and native land cover) and soil (Luvisols and Cambisols). We analyzed the following soil key indicators: CEC, soil respiration, C and N contents, and $\delta^{13}C$ and $\delta^{15}N$ signatures of soil organic C.

The average CO_2 respired from native land cover was at least 82% higher than its value from degraded land cover and was significantly higher in Luvisols than in Cambisols. Likewise, the soil organic C and N contents in bulk soil were significantly affected by land cover and soil contrasts. The average C loss in bulk soil from degraded land cover was equivalent to 49% in Cambisols and 54% in Luvisols. In both soil types, all aggregate fractions were sensitive to land degradation processes and the C loss decreased from macroaggregates to the clay + silt fraction. Compared to the native land cover, organic C loss from the macroaggregates in degraded land cover was 92% and 84%, respectively, in Cambisols and Luvisols. The soil type affected significantly the C content only in the clay + silt fraction. The C/N ratio of finer fractions (microaggregates and clay + silt) was significantly higher in degraded land cover than in native land cover, indicating greater losses of N than C during land degradation processes. The differences of $\delta^{13}C$ signatures throughout C pools between the two types of land cover suggest a relative dominance of C_3 derived C in macroaggregates and C_4 derived C in the clay + silt fraction in the degraded lands. The reduction of soil respiration and the rapid N loss in degraded land cover slowed down the humification processes of C_3 plant derived materials which were effectively dominant in macroaggregates.

1. Introduction

Sub-Saharan Africa has the highest rate of land degradation (Thiombiano and Tourino-Soto, 2007), and the per capita food production continues to decrease. Especially in its semi-arid regions, Africa is facing significant and continuous land degradation caused by climate conditions (Sivakumar and Stefanski, 2007) and land use pressure (Meshesha et al., 2012). Resulting from land use mismanagement (extensive overgrazing, excessive land clearing for extensive agriculture and fuelwood) and subsequent erosion processes, land degradation can lead to the formation of bare soils that became encrusted and unproductive (called *zippelés*). In fact, the depletion of organic matter due to loss of vegetation cover leads to the destruction of soil aggregates and to the dispersion and redistribution of soil particles by erosion (Casenave and Valentin, 1989). These processes have ultimately resulted in surface crusting and the compaction of a thin surface layer that prevents the natural regeneration of vegetation (Valentin and Bresson, 1992). The successional stages of the various surface crusts help to identify the degree of soil degradation. Particularly, surface crusts of the "erosion type" exhibit the first stages and the restoration of soil structure by vegetation remains possible (Valentin and Bresson, 1992; Schmidt et al., 2010). Nearly 24 % of the soils of semi-arid Burkina Faso has been reduced to *zipellés* (Zougmoré et al., 2003).

It is generally recognized that land degradation leads to losses of soil organic C and N stocks (Dlamini et al., 2014), and thereby to the further loss of productivity and of the ability to provide several other ecosystem services (UNEP, 2012).

Yet, soil organic C is heterogeneous and comprised of a gradient of pools that differ in physical and chemical properties, decomposability and turnover (Six et al., 2002; von Lützow et al., 2007). For this purpose, several fractionation schemes have been developed to isolate and analyze soil organic C pools. Physical fractionation of soil organic C has been widely employed in studies of land cover–land use effects in

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agricultural systems to detect changes in soil organic C pools based on different compositional fractions (Solomon et al., 2000; Liao et al., 2006a; Beheshti et al., 2012). The identification of sensitive fractions may serve as an indicator for shifts in soil organic C during land degradation processes.

Stable carbon isotopic analysis may be used for tracing the origin of organic carbon in order to understand the impacts of vegetation change (Boutton et al., 1998; Zach et al., 2006; Vågen et al., 2006). Substantial changes of $\delta^{13}C$ signatures in soil organic C can be recognized as a difference of the contribution of the C_3 (trees and forbs) and C_4 (savanna grasses) photosynthetic pathways to net productivity and resilience of C pools during the land cover change (Zach et al., 2006). It has been demonstrated that the photosynthetic pathway (Wynn and Bird, 2007) as well as the mineral composition of the soil (Bruun et al., 2010) are affecting the turnover of organic matter. Likewise, it has been recognized that the soil organic C dynamics are strongly affected by nitrogen availability and biological activity (Gärdenäs et al., 2011; Knicker, 2011).

The soil C pool dynamics and their determinants in the general context of land degradation are poorly investigated in semi-arid Africa. To determine the resilience of soil organic C pools during land degradation processes, we compared the magnitude of C and N changes in bulk soil and aggregate fractions according to contrasting types of land cover (degraded land and native land cover) and soil (Luvisols and Cambisols). It was hypothesized that soil aggregate fractions are better indicators of land degradation processes than bulk soil. The specific objectives of this study are: (i) to compare the magnitude of soil organic C and N differences in bulk soil and aggregate fractions between degraded land and native land cover, (ii) to test differences in the $\delta^{13}C$ and $\delta^{15}N$ signatures of soil organic C among aggregate fractions, and between degraded land and native land cover, (iii) to highlight the influence of soil type on soil organic C stabilization during land degradation processes.

2. Material and method

2.1. Study area

The study area is located in northern Burkina Faso and characterized by semi-arid climatic conditions with an average annual precipitation ranging from 450 to 500 mm and with a single dry season of 8–9 months (October–May). The long-term average of annual temperature varies from 22 °C for the colder season to 38 °C for the warmer season. The basic vegetation is mainly composed of grasses (C_4 photosynthetic pathway) and woody species (C_3 photosynthetic pathway). The prevailing land use systems are characterized by extensive grazing and agriculture that cause the degradation of land cover. The time scale of degradation leading to "erosion type" surface crusts is variable depending on the specific environmental conditions. It is estimated to be 30–40 years in selected sites according to a local population survey of 15 persons per site.

2.2. Site selection

We selected two sites characterized by different soil types and land cover (degraded land and native land cover). This selection was based on visual analysis of Spot images (November 2011) and completed by visual observation in the field for the delimitation of areas characterizing each land cover category within each site (Fig. 1). The degraded land cover is defined by bare soil with surface crusts of "erosion type" (Valentin and Bresson, 1992) and spontaneous vegetation cover below 5 % (*zipellé*). Its plant cover mainly consists of patchy grasses. The native land cover has natural vegetation covering more than 75 % and is well-covered by grasses and woody vegetation. The characteristics of the land cover categories are given in Table 1. The two sites are both impacted by extensive grazing but have contrasting soil characteristics.

The soils from site 1 are classified as Cambisols (higher proportion of 2:1 clay minerals) with the presence of a *cambic* subsurface horizon which is identified by finer texture and higher chroma or higher value than the overlying layer (IUSS Working Group WRB, 2006). In contrast, the soils from site 2 are classified as Luvisols (higher proportion of 1:1 clay minerals) by the presence of an *argic* subsurface horizon associated with clay illuviation processes (IUSS Working Group WRB, 2006). The description of the reference soil profile for both soil types is given in Table 2.

2.3. Experimental design and soil sampling

The sampling design was based on full factorial design (2 × 2) with two contrasting soil types (Cambisols, Luvisols) and two contrasting land covers (degraded land cover and native land cover). Within each factorial feature, seven replicated plots (5 m × 5 m) were randomly sampled (Fig. 1) and soil sampling was performed in one soil profile (50 cm deep) within each plot. From each soil profile, soil samples were taken from the surface horizon (0–10 cm) at the beginning of the dry season (October 2012). In total, 28 dry soil samples were collected and sieved with a 2 mm mesh for laboratory analysis. For field respiration tests, six random subplots (radius 20 cm) within each plot were sampled for two consecutive essay dates (19–20th September 2012 at 6 h–9 h a.m.).

2.4. Field measurements and laboratory analyses

Routine soil descriptions were carried out throughout the soil profile (50 cm depth) to provide a satisfactory indication of soil nature (FAO, 2006). Field measurements of soil respiration were done on moist soil with a non-dispersive infrared gas analyzer (EGM-4 CO_2 Gas Analyzer) to record the CO_2 in the range of a few ppm with excellent stability of the signal. At the same time, additional soil parameters such as soil moisture (gravimetry method) and temperature were recorded.

Fine soil particle sizes (5 fractions) were determined for all samples using the Robinson pipette method after the destruction of organic matter with H_2O_2. The soil pH (H_2O) was measured using a combination electrode in a soil–water solution ratio of 1:2.5, cation exchange capacity (CEC) was determined by the silver thiourea method (Reeuwijk, 2002) and available phosphorus by the Bray I method (Reeuwijk, 2002).

Aggregate fractionation was used to obtain C pools (Six et al., 2002). For this purpose macroaggregates (≥250 μm), microaggregates (250 – 53 μm) and clay + silt (<53 μm) associated C were isolated from 150 g of dried 2-mm-sieved soil by wet sieving using deionized water on top of a 250 μm sieve. After gentle shaking and slaking using an analytical sieve shaker, water charged with soil < 250 μm was poured through a 53 μm sieve. The silt + clay fraction that passed the 53 μm sieve was collected by filtration. The determination of mass fraction and proportion was performed by weighing after oven-drying at 65 °C.

Bulk soil and aggregate samples were analyzed for carbon and nitrogen contents (C %, N %) as well as stable isotope ratio of the two elements, (^{13}C, ^{15}N) on an elemental analyzer-isotope ratio mass spectrometer (EA-IRMS) that was linked to an element analyzer (Carlo Erba CHN1110). The results of the isotope analysis are expressed as a δ value (‰) relative to the VPDB scale for ^{13}C and the atmospheric nitrogen scale for ^{15}N.

2.5. Data analysis

All measured variables in relation to C dynamics were examined by factor analysis using maximum likelihood to detect their relationship and pattern following two downsized dimensional factors (land cover and soil type). Pearson's product moment coefficient was generated to test the correlation between these variables.

The effects of land cover and soil types as well as their interaction were tested using ANOVA generalized linear models (GLMs) or beta regression models for proportion data. These models allow fitting a response variable by specifying a family of error distribution and a