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# Regulation of carbon and nitrogen exchange rates in biological soil crusts by intrinsic and land use factors in the Sahel area

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The occurrence and diversity of biological soil crusts (BSC) a thin soil surface layer composed of phototrophic and heterotrophic microorganisms intimately associated with soil particles, are known as strong indicators of ecosystem health and sensitivity to soil surface disturbances and are key factors in the biochemical cycling of carbon and nitrogen in drylands. However, the impact of land use on C and N budgets related to BSC dynamics is poorly understood and hinders the prediction of changes in soil fertility in response to future land use scenarios. In this study, we examined the C and N exchange rates of BSC sampled along a north-south pluviometric gradient of the Sub-Sahel, which provides evidence of increasing human land pressure, leading to a gradient in fallow duration and trampling intensity. We demonstrate that the net and gross photosynthesis by BSC significantly increases with fallow duration and a reduction of trampling intensity, thus affecting BSC fine particles and relative water content. Conversely, no effect of land use was found on N fixation or mineralisation rates, which are instead regulated by the N availability within the crust. Simple statistical models were derived from the relationships between C exchange rates and BSC intrinsic characteristics related to soil surface disturbances. The proposed statistical models were tested for C gas exchange with independent data obtained from a new BSC dataset sampled in Burkina Faso and Niger. A simple equation using BSC fine particle content as a unique variable was found to explain between 60 and 70% of the gross photosynthesis. Our findings will help in mapping photosynthesis and estimating the contribution of BSC to the carbon budget at a regional scale in the dryland area of the Sahel and to further testing of land use change scenarios.



## 1. Introduction

Arid and semi-arid environments, which cover more than one-third of the Earth's terrestrial surface, are among the most responsive and inherently vulnerable environments to climate and human-originated disturbances (Weltzin et al., 2003). Following the recently published paper of Elbert et al. (2012), cryptogamic covers, which are composed of photoautotrophic communities, lead to a net C uptake (photosynthesis minus respiration) of approximately 7% of carbon net primary production by terrestrial vegetation. In total, the deserts of the world are estimated to contain 56 $\times$ $10^{12}$ g C as cyanobacterial biomass. Therefore, these covers are major players in the global biogeochemical cycles of C and N in drylands (Elbert et al., 2012). In such environments, cryptogamic covers are mostly composed of biological soil crust (BSC), i.e., a thin soil surface layer made up of phototrophic and heterotrophic microorganisms intimately associated with soil particles. Due to the ability of their constituents, mostly cyanobacteria, to withstand high temperatures, radiation and low water potential and to remain dormant in a dry state for long periods of time (Garcia-Pichel and Pringault, 2001; Miralles et al., 2012), BSCs impact nutrient and water dynamics, thus playing a crucial role in soil stability and soil hydrologic processes (Lange et al., 1992; Zaady et al., 2000; Pointing and Belnap, 2012).

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One of the major ecological roles of BSCs is their contribution to C and N cycles, which results from the balance between photosynthesis and N fixation and the mineralisation of C and N by heterotrophic respiration. The rates at which these ecosystem services are provided depend on abiotic and biotic factors. Moisture and temperature were reported as important abiotic drivers of BSC C and N rate exchanges (Grote et al., 2010; Lindo et al., 2013), underscoring the importance of explicitly considering BSC in climate models (Elbert et al., 2012). However, in arid environments such as the Sahel, climate change also has direct effects on population behaviour and land use. Since the late 1960s, for example, the Sahelian region has regularly experienced below average rainfall and long dry periods, with dramatic consequences for water resources and vegetation cover, triggering soil erosion (Mougin et al., 2009). Furthermore, land cleared for cropping has increased and fallow duration has been reduced with an increasing livestock population, contributing to the impoverishment of soil fertility and to increased grazing pressure on rangelands (Hiernaux et al., 2009). The occurrence and diversity of BSCs are strong indicators of ecosystem health in drylands (Jones, 2000), as these factors have been reported to be very sensitive to soil surface disturbances such as grazing, trampling, cultivation and fallow duration (Malam Issa et al., 2009; Dojani et al., 2011; Gomez et al., 2012; Daryanto et al., 2013). However, the impacts of such disturbance on C and N exchange rates in BSC communities remain poorly studied, particularly in African ecosystems (Thomas, 2012).

In the Sahel area, BSCs commonly occur on pre-existing physical crusts (sieving, erosion and runoff crusts), depending on both the regional and local geomorphologic characteristics and the texture of the soils (Bromley et al., 1997; Malam Issa et al., 1999; Graef and Stahr, 2000). Such characteristics have also been observed in other arid environments of the world (Cameroon and Blank, 1966; Eldridge et al., 2000). The high frequency of trampling, grazing and cultivation occurring in the Sahel has been recognised as the cause of fine particle (clay + silt) and nutrient losses from the soil surface (De Rouw and Rajot, 2004; Valentin et al., 2004; Neff et al., 2005; Barger et al., 2006). For instance, in sandy Sahelian soils, Valentin et al. (2004) showed that cultivation destroys the erosion crusts that develop during fallow periods in response to dust deposition and colonisation by cyanobacteria. Moreover, the proportion of fine particles tends to decrease during cultivation, whereas it increases once the land is returned to fallow. In total, land use change is accompanied by soil textural variations that may have tremendous importance for BSC development and functioning in dryland areas. Recently, Williams et al. (2013) suggested that in the Mojave Desert, the underlying commonality among crust types is the particle size distribution of the soil profile. Therefore, particle size, which is known to control the stability, surface roughness and pore size of arid soil surfaces and to thus constrain the development of microbial crusts, may impact the functioning of these crusts (e.g., the extent to which C and N exchange rates occur in BSC) and might help predict these exchange rates.

The objective of the present study is to highlight the impact of soil surface disturbances on the C and N cycling of biological soil crust and to explore how these ecological functions may change under future land use. We hypothesized that intrinsic characteristic of BSC would impact C and N exchange rate and that simple statistical model, while crude, could be derived from these relationships to estimate photosynthesis and N fixation from BSC encountered in dryland area of Sahel. To do so, we examined the characteristics and C and N recycling of BSCs and underlying soils from the Sahelian part of Western Niger. Samples were taken along a north-south pluviometric gradient of the Sub-Sahel following a gradient of increasing human land pressure, as reflected by decreased fallow duration and increased trampling intensity. A simple statistical model was derived from the obtained data to estimate photosynthesis and N fixation from BSCs encountered in the dryland area of the Sahel. The proposed statistical models were kept as simple as possible and were tested for C gas exchange with independent data obtained from a new BSC dataset of samples from Burkina Faso and Niger.

## 2. Materials and methods

### 2.1. Sampling strategy and study sites

Sampling was conducted at two different times. The first set of biological soil crust and underlying soil samples was taken in February 2009 in Western Niger (Fig. 1) to establish the relationships between the intrinsic characteristics of BSC and C and N exchange rates; these data were used to derive a statistical model. The second sampling was performed in autumn 2011 in Burkina Faso and Niger with the aim of testing the statistical relations on independent samples.

The first sampling was performed in two zones located in Western Niger along the bioclimatic gradient, whose latitude stretches across from the Sahel to the north to the Sudano-Sahel to the south (Fig. 1). Both zones are characterised by a single rainy season lasting from May to mid-October and a consistent north-to-south gradient of 100 mm per degree, i.e., 1 mm per km. The two zones support agricultural and pastoral activities. The first study zone is located near the village of Banizoumbou, 70 km east of Niamey, and lies on residual aeolian sand dunes covering Tertiary fluvio-lacustrine deposits (Fig. 1). The annual rainfall is estimated to be 520 mm/year based on data collected from 1989 to 2008 across the south-north rainfall gradient. The second area is located near the village of Tamou in the south, approximately 100 km from Niamey, and lies on weathered granitic material covered by aeolian sand dunes (Fig. 1). The annual rainfall in the Tamou area is estimated to be 630 mm/year based on data collected from 1989 to 2008 across the south-north rainfall gradient. We selected three sites near Banizoumbou – Site 1 (sample C1), Site 2 (samples H1 to H4) and Site 3 (samples M1 and M2) – and one site near Tamou, designated as Site 4 (samples S1 and S2) (Table 1).

The soils in both areas are similar due to the rather uniform aeolian sand deposits on different geological substrata. These soils are poorly aggregated sandy to sandy loam soils with a low organic matter content (less than 1%). These soils are prone to physical crusting, i.e., the formation of a compacted structure at soil surfaces favourable to runoff and interrill erosion (Valentin, 1996). The type of physical crust was determined for each sample following the procedure of Valentin and Bresson (1992) using a 30× Laboratory Binocular Microscope and three replicates. The criteria were the particle size of the upper micro-layer (>50 μm for structural crusts, referred to as ST, and <50 μm for erosion crust (ERO) and sedimentation crust (SED)). The erosion crusts are composed of a thin (<1 mm) layer, whereas the sedimentation crusts are thicker and are composed of finer materials at the top and coarser materials at the bottom due to the sedimentation of particles in still water. The upper layer is often curled up.

This first sampling plan was based on two main criteria: land use (type of use, fallow duration and trampling intensity) and the underlying physical crust types (Table 1). The fallow duration was readily assessed in Banizoumbou (Sites S1, S2 and S4), which is a long-term observatory. For the other sites, the fallow duration was based on field evidence (crop residues indicating a 1-yr fallow in S4; the extent of vegetation regrowth in S7). At the other bush and rangeland sites, where ancient cropping is inconspicuous, the fallow duration was arbitrarily fixed at 50 years. The fragile crusts that largely cap the Sahelian sandy soils are readily broken by