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Pioneering assessment of carbon stocks in polder soils developed in inter-dune landscapes in a semiarid climate, Lake Chad

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ABSTRACT

In semiarid Sahelian region, the dynamics of soil organic carbon (SOC) and water are key to sustainable land management. This work focuses on the behaviour of carbon. A total of 33 soil profiles in four polders, ranging from 10 to 65 years in age, were sampled, analysed (0–1 m), and matched with marsh soil profiles in recent sediments considered as reference (t_0) for carbon stocks determination. SOC and soil inorganic carbon (SIC) stocks show a spatial variability between polders. SOC stocks were t_0 200 ± 0.8; t_{60} 183 ± 34; and t_{65} 189 ± 1.1 MgC·ha^{-1}, whereas the SIC stocks were negligible. These results show the highest stocks of soil carbon observed for this climatic region. The SOC stocks were also calculated for the equivalent soil mass at a defined depth (0–0.3 m); the corrected calculation of SOC stocks (S_{corr}) for 2450 Mg·ha^{-1} of equivalent soil mass is t_0 64 ± 1.9, t_{60} 59 ± 9.8, and t_{65} 53 ± 2.2 MgC·ha^{-1}; the stocks decrease by −7.8% and −17.2% from t_0 to t_{60} and t_{65}. Carbon was inherited from the pre-existing marsh and the polders have conserved high stock values.

1. Introduction

Soil constitutes an important reservoir of organic carbon in the biosphere. The atmospheric C compartment is estimated at 750 Gt, which is considerably lower than the soil C compartment. The latter is estimated, at a depth of 1 m, to 2500 Gt (Lal, 2004), of which 62% (1550 Gt) is organic (SOC) and 38% (950 Gt) is inorganic (SIC). In the top 30 cm, it is estimated at about 684 to 724 GtC (Powlson et al., 2011). In terms of land management, soil organic carbon (SOC) dynamics raise two major issues: one is a global – climate change and changes in land use and their effect on greenhouse gases (Gitz and Ciais, 2003) – and the other is local and relates to soil fertility strictly associated with food security. Globally, the challenge is to maintain or even increase the amount of carbon stored in soil and vegetation (Robert and Saugier, 2003). Indeed, element stock in soils, including carbon (C), are constantly changing with the effect of a range of natural and anthropogenic factors such as climate, hydrology, geology, vegetation, biological activity, local impacts of land use, and changes in agriculture or silviculture (Brossard and López-Hernández, 2005; Follain et al., 2007). Considering all of these factors is generally impossible. Redistribution of elements such as carbon brought about by these processes has a significant impact on soil C stocks by changing their distribution locally. In the literature, different estimates of decrease in soil organic C stocks have been reported, resulting from cultivation of natural agroecosystems (either grassland or

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natural vegetation) in a wide range of climatic conditions and different years following land use conversion (Fujisaki et al., 2015). For example, according to Martinez-Mena et al. (2008), carbon stocks in agricultural soils can fall by 30 to 50% of their initial level after 50 to 100 years of cultivation, while Manlay et al. (2004) reported a decrease of 50% after 15 years of cultivation in the West African savannah ecosystem. The annual net loss coefficient under rainfed cultivation compared to the initial ecosystem is around 4.7% in sandy soils and 2% in clay soils (Pieri, 1989; Serpantié et al., 2004). The available data suggest that C in continuously cultivated topsoil is more sensitive to land use change.

In dry tropical environments, soils have low C contents (Jones et al., 2013) due to limited availability of water, which restricts plant productivity, which in turn is the main source of SOC. From long-term data on tillage and cropping system experiments in Chad, Pieri (1989) reported SOC annual losses of 1.2 and 0.5 $gC{\cdot}kg^{-1}{\cdot}yr^{-1}$ with cereal cropping and 2 and 4 years of fallow. The extreme semiarid climatic conditions make this ecosystem fragile, and therefore soils are particularly prone to degradation during the implementation of more intensive land management practices, overgrazing and frequent fires. In the semiarid Sahelian region, the dynamics of SOC and water are keys to sustainable land management aimed at maintaining fertility, stability and soil productivity (Pieri, 1989). Soils have low organic C contents, 4.3 $g{\cdot}kg^{-1}$ in 0–40 cm (Manlay, 2000) and stocks to 1 m deep represent 20 to 30 $MgC{\cdot}ha^{-1}$ (Jones et al., 2013), part of which, a few $Mg_C{\cdot}ha^{-1}$, are lost annually. However, on a local scale, C stocks are poorly known, despite the various issues they represent in terms of maintaining soil properties, food security, greenhouse gas emissions, and decision support.

Agriculture in the northeast Lake Chad landscape is developed on polders created on marshland initially developed in inter-dunes. These polders are an ancient arm of Lake Chad, resulting from the regression of lake waters due to the climate variability that prevailed during the Holocene and the recent decades in the Sahel region (Schuster et al., 2009). Hydro-agricultural schemes have been put in place to keep agriculture safe from floods and to store and distribute irrigation water. Taking into account climate variability, they represent an interesting agro-economic alternative for Sahelian farmers, allowing them to develop food security or secure annual revenues. In this context, soils are subject to intensive exploitation of three harvests per year, the rotation is based on cereal (maize/wheat) and market gardening (fenugreek/bean/tomatoes). There are different levels of intensification and practices that could be achieved in rainfed agriculture; irrigated agriculture during the dry season and all technical strategies must be included in a hydro-agricultural project adapted to the needs and capabilities of local societies. This agricultural intensification constitutes one of the possible answers to farmers' adaptation to climate variability in the region. For over 60 years, polders were subject to intensive exploitation without organic stock management, organic input or any other technical concern for their conservation. According to previous observations (Pias and Guichard, 1960; Pias and Sabatier, 1965), after more than ten years of intensive cultivation (three harvests per year, crop residues being exported out of the polder), the organic matter content decreased from 100–130 to 60–70 $g{\cdot}kg^{-1}$ in the surface horizon (0–0.2 m); those losses represent an annual loss coefficient of organic matter content equivalent to those observed in sandy soils (4.7%$\cdot y^{-1}$) and clayey soils (2%$\cdot y^{-1}$) (Pieri, 1989; Serpantié et al., 2004).

In semiarid regions, lowland soils are strategic for agriculture providing food security. One question is to know if the SOC changed during time, as the system is based on irrigation on Fluvisols. The present study aims for the first time to estimate soil C stocks in these polders. The approach emphasizes an inventory of one polder's chronosequence (synchronic approach). In this study, we aim to assess the SOC stocks in polders over a period of 65 years of cultivation and to compare them to a reference marsh soil.

2. Materials and methods

2.1. Study area

Lake Chad is an endorheic basin partitioned in two sub-basins. The study is located in its southern part, which is the actual hydrologic basin of the lake and receives water from the perennial Chari and Logone rivers (Olivry et al., 1996). The studied area is located on the northeastern shore of Lake Chad in the Bol area, northwest of the Sahelian zone of Chad between 12° 20′ and 14° 20′ north latitude and 13° and 15° 20′ east longitude (supplementary data, Fig. S1). The inter-dune depressions are occupied by a Holocene, 10- to 15-m-thick, lacustrine deposit (Labdé series) (Dieleman and De Ridder, 1963; Pias, 1970; Schuster et al., 2009). The nature of the sediments is variable, but in general the texture is clayey to silty–clayey; the sequence from the base to the top is formed by a grey–green clay–silt deposit, more than 3 m in thickness; a 3-m-thick grey to grey–blue clay layer, a 1- to 4-m-thick clayey deposit, whose clays present a polyhedral structure, with carbonate accumulation in the upper part of the deposit; the later deposits are comprised of a sequence of clays and organic matter-enriched clays in the upper last meter, with variable silt contents.

The climate is classified as semiarid to arid Sahelian (BSh, hot steppe, Köppen-Geiger climate classification, Peel et al., 2007) characterized by the alternation of a long dry season and one short rainy season concentrated in three months, from July to September. The average annual temperature is high, 28 °C, mean annual precipitation is between 550 and 200 mm. Potential evapotranspiration (PET) is 2284 $mm{\cdot}yr^{-1}$ (average for period 1960–1977), so the P/PET ratio is between 0.09 and 0.2, and characterizes this arid environment sensitive to climatic hazards. This PET was measured on a polder by the Thornthwaite device (Olivry et al., 1996).

Five soil sites were selected for this study depending on their age after "polderisation":

- a marsh on recent sediments (t_0) on an adjacent part of the t_{10} polder to determine the soil C as a reference;