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**Carbon sinks in small Sahelian lakes as an unexpected effect of land use changes since the 1960s
(Saga Gorou and Dallol Bosso, SW Niger)**

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Abstract

For several decades, global change has resulted in an increase in runoff in the Sahelian belt, provoking major changes in the quality and quantity of sediments transported by drainage networks. One of the astonishing consequences is the establishment of numerous permanent lakes. The origins of particulate organic matter (OM) preserved within lacustrine sediments of three lakes were investigated by coupling optical observations (palynofacies) and bulk geochemistry (Rock-Eval 6 pyrolysis). An initial estimate of particulate organic carbon (OC) stored in these lacustrine sediments was assessed. Soil organic matter (SOM) was sampled from the surface (0-10 cm) of various land-use and land-cover areas and was characterized and compared with sedimentary organic matter. Our results reveal that Lake Tankalawal is subjected to high autochthonous organic sedimentation (TOC ranges between 3.0 and 10.0 wt. %), while lakes Bangou Kirey and Bi are characterized by weak sedimentation of non-indigenous OM originating from the soil erosion and shore vegetation (TOC < 3.0 wt. %). In sediments, the effects of early diagenesis on the OM induce a loss of labile and aquatic OM but also a significant loss of terrestrial OM, which is supposed to be more resistant than its aquatic counterpart. Both the preservation of OM in top sediments and the relative preservation of terrestrial OM impact the OC storage in lakes. Indeed, OC storage in lacustrine sediments (Lake Bangou Kirey) was two to seven times higher than the OC storage in Sahelian soils, where greater contributions of terrestrial OM to sedimentary OM are associated with lower OC storage in lacustrine sediments. For lakes Bangou Kirey and Bi, OC accumulation rates were also assessed; due to the identification of a sedimentary limit corresponding to the establishment of permanent lakes dated earlier 1960s. High OC fluxes were estimated and ranged between 104 and 213 g OC m⁻² yr⁻¹. Compared with other OC accumulation rates for various African lakes, these high values are similar to those calculated for reservoirs and are related to anthropogenic pressure, soil textures favoring erosion, and proper physical and chemical conditions for OM preservation in sediments. Accordingly, in these Sahelian environments that are generally viewed as non-efficient in storing OC, we claim that global change could promote a new OC sink. If other similar studies reinforce our assertion, then regional C budgets should be revisited.

Keywords: particulate organic matter, carbon sink, soil erosion, lakes, Sahel, Global Change

1. Introduction

Since the 1960s, Sahel has been subjected to a spectacular climatic shift toward a strong deficit in precipitation with a decrease of 20 to 50 % (e.g., Lebel et al., 2009; l'Hote et al., 2002). Simultaneously, this region has experienced vigorous population growth, from 1.5 % to 3.0 % per year in the period from the 1950s to the 2000s (e.g., Raynaut, 2001, ECOWAS-SWAC / OECD, 2007). The combination of climatic shifts and anthropogenic pressure are responsible for drastic environmental changes in this harsh environment (Niang et al., 2007). Southwestern part of Niger is not exempt from these changes. The increase in runoff, which modified the water budget in watersheds, was broadly examined (e.g., Cappelaere et al., 2009; Descroix et al., 2012; Leblanc et al., 2008). In particular, the causes of this increase in runoff were investigated in the context of changes in land use accompanied by progressive soil crusting. Surprisingly, despite the persistence of desertification, the regional water table, regionally named "le paradoxe de Niamey," has risen (Leduc et al., 1997; 2001). This rise of the water table has involved the establishment of numerous permanent or ephemeral small lakes throughout the Sahelian belt (e.g. Cappeleare et al., 2009; Desconnets et al., 1997).

The intensification of surface runoff due to land use changes have triggered some changes in the budget of sediments within watersheds, which can be expressed by (i) a rise in erosion intensity, (ii) changes in erosion sources and (iii) an increase in sediment accumulation rates in lakes. The increase of cultivated areas implies that there are sediment and nutrient supplies in ponds and lakes (Descroix et al., 2012 and references therein). These changes also affect the quality and the amount of terrestrial organic supplies (allochthonous OM) carried by rivers to lakes and the primary organic productivity in lakes (autochthonous OM). Sahelian soils and sediments have been considered as weak C sinks and are poorly

studied (Feller et al., 1991; Fofana et al., 2008); these recent environmental changes may significantly modify the organic C budget and exchange between terrestrial and aquatic environments.

The goal of this preliminary study was to focus on these new lacustrine C reservoirs by proposing the first quantification of OC stocks in lacustrine sediments. For this purpose, three representative lakes of the surrounding of Niamey, showing variable anthropogenic pressures, variable sedimentary dynamics and variable water quality levels were examined. We first characterized the optical and geochemical aspects of the OM to seek its origin, weathered stage and the ability to record these environmental changes. Next, OC stocks in Sahelian sediments were assessed and compared with the surficial Sahelian soil OC (SOC) storage, as well as with the OC storage potential of other African lakes.

2. Local settings and sampling strategy

2.1 Geographic and environmental settings

The limnic complex of Saga Gorou, including Lakes Bangou Kirey and Bi, and the lake Tankalawal are located in southwestern part of Niger (Fig. 1). The regional climate is semi-arid with yearly precipitation ranges between 400 - 700 mm and a potential evapotranspiration of 2500 mm (D'Amato and Lebel, 1998). The bedrocks consist of unconsolidated material composed of silts and clays from the Tertiary Continental Terminal (Greigert, 1966), and are overlaid by Quaternary eolian sands. These thick sandy deposits cover the valleys and can form dunes over the Continental Terminal plateau. Dry and sandy valley and plateaus are considered as the main geomorphic units in this catchment representing 78 % and 22 % of the surface catchment area respectively. Soils consist in tropical ferruginous soils slightly leached on sands (Cambic Arenosols, IUSS-WRB, 2006) and little evolved tropical soils exhibiting a ferruginous facies (Skeletal Leptosols, IUSS-WRB, 2006) developed on plateaus (Gavaud, 1977). This latter soil type is characterized by a single horizon several decimeters thick and results in the dismantling of the ferruginous armor of the plateaus. These specific conditions ruled the initial vegetation cover and the crop management, which is comprised of three distinct units (d'Herbès and Valentin, 1997): tiger brush

vegetation is developed on plateaus, whereas arable land and rare fallow overlay sandy soils in valleys. However, the recent changes in land use, particularly in the surrounding of cities, involves a complete disappearance of tiger brush since 2009 and fallows land to the benefit of barren surface on the plateaus, and crop land in the valley, favoring soil crusting (Abdourhamane Touré et al 2010; Descroix et al., 2012). This crusting is also imputable to the increase in eolian and water erosion of sandy soils, which truncate soil profiles up to horizon B.

2.2. Soil sampling strategy

Sources of OM in lacustrine sediments can be simplistically described as a melange of OM from the catchment (mainly soils) and OM from aquatic production. It is thus important to perform a representative sampling within the catchment of Saga Gorou taken into account major land-uses and land-covers, corresponding to as many soil and SOM types likely to feed the lake. Accordingly, selected plots were based on a combination between land-use and the two main geomorphic units (see section 2.1). In detail, plots from millet crops and crusted surfaces (Casenave and Valentin, 1992), representative of dry valley and counting for 55% and 19% respectively in the total catchment area (Abdourhamane Touré et al., 2010) were sampled. In plateau, the land-cover consists only in crusted surface (22 %).

Referring to numerous studies dealing with SOC topsoil distribution in Sahelian soils (table 1 and references therein), Sahelian topsoils contribute for a large part of the total SOC storage (e.g. Batjes and Sombroek, 1997). In addition, topsoils are likely to be eroded during runoff events so that its OM can join the drainage network and finally the lake and, in this area. In this regard, the first ten centimeters of topsoils were considered according to these three main OM sources and for each of them, two plots were sampled (Fig. 1b). Accordingly, two sampling plots (1m²) were conducted on plateaus (profile P and PP, 4 samples) and four were conducted in sandy valleys (millet crops: profiles M and MM, 4 samples; crusted surfaces: profiles C and CC, 4 samples). For each sampling, three replicates were made and placed few meters away from others. To ensure the representativeness of organic matter quality, the counterparts of each of these replicates were mixed together.

2.3. Lakes

2.3.1 Geography and characteristics

Three lakes were cored: two (lakes Bangou Kirey and Bi) belong to the Saga Gorou limnic complex (13°28'-13°31'N; 2°11'-2°15'E; Fig. 1B), which comprises a group of lakes sometimes filled by sand. These lakes are located in some topographic depression within small paleo-valley named Kori of Ouallam that was formerly linked to the Niger River. The third lake, named Tankalawal, is located in another dry but larger valley, known as Dallol Bosso (13°03'12"-13°03'28"N-2°51'43"-2°51'48"E; Fig. 1.C), this ancient river was an affluent of the Niger river and is now composed by numerous lakes, including Tankalawal.

Lake Bangou Bi (Fig. 1B), occupying 0.06 km², is oligotrophic and receives detrital input carried out by some gullies (Abdourhamane Touré, 2011) and maximal water depth reaches 3.5 m during the field study. The catchment (5 km²) is subjected to severe anthropogenic pressure, beginning in earlier 1960s with an extensive development of market crops (millet) to the detriment of natural tiger bush and fallows (Abdourhame Touré et al., 2010). Lake waters show neutral pH (pH = 7.75) and are mineralized (conductivity = 275 µS.cm⁻¹) corresponding to the input of water table. Lake Bangou Kirey (Fig. 1B) is supplied both by the ground water and by a network of gullies that drain an area of 60 km². Maximal water depth reaches 5.3 m during the field study and waters are acidic (pH = 5.6), poorly mineralized (conductivity = 30 µS.cm⁻¹) and exhibit a chlorine to sodic facies. Lake Tankalawal (Fig. 1C) occupies 0.02 km² and is essentially fed by the ground water ~~table~~ and sediments come from the shore. Maximal water depth reaches 0.2 m and the water is mesotrophic to eutrophic, basic (pH = 7.75), strongly mineralized (conductivity = 930 µS.cm⁻¹) and shows a chlorine to sodic facies.

2.3.2 Sampling design

In this region of Sahel, most of these permanent lakes occupy the rivers bed of some ancient drainage networks and their impoundment is due to change in land uses and anthropogenic activities (Cappeleare et

al., 2009; Desconnets et al., 1997). Several arguments, as aerial scenes observations and field enquiries involving local farmers (Abdourhamane Touré, 2011, Abdourhamane Touré et al., 2010), tend toward a lakes impoundment starting in 60's. This also corresponds to the strong increase in groundwater resource (+150 %, Leduc et al., 2001). Saga Gorou limnic complex can be considered as a good example of these regional changes in hydrology as it consists of permanent / ephemeral lakes and of lakes fully filled by detrital material. Lake Tankalawal was ~~also~~ selected because of its organic sedimentation which differs from the Saga Gorou limnic complex. After a bathymetric survey, coring location was selected regarding two conditions: the maximal water depth of the studied lake and being away from detrital fans to avoid coarse material as sand in sediment. For each lake, one core was sampled with a Gravity Corer UWITEC (PVC-liner diameter of 63 mm, with liner length ranges between 100 to 250 cm).

Core BB2 from lake Bangou Bi (140 cm length, (13°30'30"N; 2°12'3"E, Fig. 1.B) exhibits lithological characteristics have distinguished two sedimentological units: a sandy unit from the bottom of the core to 65 cm (named unit 1) and unit 2 (from 65 cm to 0 cm), which is silty to loamy. For organic matter analyses, a sampling level of 10 cm was applied to this core. The core BK-08-02 from the lake Bangou Kirey (13°30'30"N, 2°13'35"E, Fig. 1.B) exhibits lithological characteristics have distinguished two sedimentological facies: a non-laminated lower unit (216 – 120 cm) from the bottom and an upper unit (120 – 0 cm) showing an alternating of bright and dark red laminae. Dark laminae consist of alternating bright and dark fine laminae. Six samples, corresponding to the main sedimentary facies observed in this core, were collected in the lower unit (208, 196, 192, 186, 176 and 146 cm depth) and 3 samples were collected in the upper unit (33.8, 32.1 and 30.5 cm depth). The core TK1 (13°03'21"N; 2°51'46"E, Fig. 1) consists of a single unit of 60 cm length and exhibits loamy sediments. A sampling rate of 5 cm was applied.

3. Methods

3.1. Geochemistry of sedimentary OM (Rock-Eval 6 pyrolysis)

Rock-Eval 6 pyrolysis is now widely used for the study of soil OM (e.g., Di-Giovanni et al., 1998, Disnar et al., 2003; Copard et al., 2006; Sebag et al., 2006a) and OM preserved in lacustrine sediments (e.g., Di-Giovanni et al., 1998, Noel et al., 2001; Jacob et al., 2004; Hetényi et al., 2010; Boussafir et al., 2012). Pyrolysis was performed using an RE6 pyrolyser (turbo model, Vinci Technologies®, France) on sediment samples that were previously dried at 40°C in an air oven and were homogeneously crushed. The first step in this method consists of pyrolysis of an 80-100 mg sample from 200 to 650°C under nitrogen with a heating rate of 25°C.min⁻¹. Released hydrocarbons were continuously quantified using a Flame Ionization Detector (FID), while CO and CO₂ were quantified using Infra-Red cells. The pyrolysate was then oxidized under air atmosphere from 400 to 750°C with a heating rate of 25°C.min⁻¹. During this second step, CO₂ and CO were continuously quantified (see also principles in Lafargue et al., 1998). The exploitation of signals derived from the pyrolysis and oxidation stages provides the total organic carbon (TOC, expressed in wt. %), as well as certain parameters of the quality of organic matter. Among these parameters, particular attention was paid to the amount of hydrocarbon (HC) released during the pyrolysis stage (S₂ signal, expressed in mg HC. g⁻¹ sediment), which can also be related to the TOC (HI index, expressed in mg HC. g⁻¹ TOC). HI is considered to be a good indicator of the degree of hydrogenation of OM (Lafargue et al., 1998). S₃ and S_{3'} signals (expressed in mg O₂. g⁻¹ sediment) reflect the release of CO₂ and CO, respectively, during pyrolysis and provide the oxygenation degree of OM (OI index, expressed in mg O₂. g⁻¹ TOC). We have also used the TpS₂ parameter (expressed in °C) corresponding to the pyrolysis temperature at which the maximal amount of hydrocarbons is released. This parameter provides information on the degree of transformation recorded by organic components during OM processes (e.g., early diagenesis and pedogenesis) and on the nature of some organic components (e.g., lignin, cellulose, sugars, proteins and humic compounds, see Carrie et al., 2012). In this work, HI vs OI diagram, named pseudo Van Krevelen diagram, was commonly used to highlight the origin of OM and its degradation state (e.g., Disnar et al., 2003). By analyzing pure biochemical and biological standards, as lignin, carbohydrates and phytoplankton, Carrie et al. (2012) have completed the

interpretation of this diagram by abacus a series of some limit values of HI/OI ratio where these compounds are likely predominant (see Carrie et al., 2012 for further details).

3.2. Organic petrography (palynofacies method)

This optical method consists of the study of thin slides of a total assemblage of particulate OM previously isolated from sedimentary rocks using acid digestions (HCl / HF). Initially developed by Combaz (1964), this technic is frequently used for the characterization of particulate OM in lacustrine sediments (e.g., Sifeddine et al., 1995, Noel et al., 2001, Jacob et al., 2004) and in soils (e.g., Sebag et al., 2006b, c, Graz et al., 2010). This approach involves the characterization of different organic constituents showing a large diversity in terms of size, texture, color, opacity and recognizable biological structures (cf. Fig. 2, see also Tyson, 1995 for details). This method provides the origins of the OM (e.g., higher plants or algae), the related production area (bedrocks, soils, or aquatic environments) and the degree of transformation (e.g., during pedogenesis). Here, optical observations and investigations were performed using a DMR XP Leica microscope upon a transmitted light mode, and relative surface quantifications were performed with a 50x objective. A counting of 500 points is required to statistically reflect the abundance of each class of palynofacies. The classification and the characterization of the origin of organic constituents were derived from the work of Tyson (1995), revisited by Sebag et al. (2006c). In this study, phytoclasts consist of (i) ligno-cellulosic (LC) debris showing variable degradation states (from translucent to degraded LC, named TLC and DLC), (ii) opaque particles (OP) obtained either from the incomplete combustion or severe oxidation of LC particles, (iii) gelified particles (GP) originating from an earlier gelification process of OM inside the higher plant cells under aquatic conditions. In this study, amorphous constituents of organic matter showing diffuse edges with any recognizable biological structures are separated into three classes: (i) brownish AOM with numerous black inclusions (brAOM) originating from bacterial degradation of phytoplanktonic biomass in aquatic environments, (ii) black AOM (blAOM) originating from an organo-mineral matrix with amorphous and LC debris and (iii) reddish AOM classically defined

as the result of severe pedogenesis of OM. These two latter classes are combined here under the term of terrestrial AOM (TAOM).

3.3 OC storage and accumulation rates

In Sahel, deposition environments are scarce and erosion products can be stored in new permanent lakes (Descroix et al., 2012). These new deposit areas can also significantly change the OC budget because lacustrine sediments can contain a significant amount of ~~host~~ OC (i) from aquatic productivity and (ii) from the catchment (SOC). A part of this later OC can be mineralised during OM processes in soils and the remain, escaping from these processes, further deposited in lakes. In this respect, lakes can function as a source and sink of carbon for aquatic OC and as a sink of carbon for SOC. However, any study was hitherto assessed the ability of such lacustrine reservoirs to store OC. Therefore, this study proposes a first estimate of the OC stocks by considering a thickness of 10 cm of core to compare these stocks with those from neighboring studied soils. OC stocks (OC) were estimated using the following equation:

$$(1) \text{ OC} = \text{dBD} \text{ TOC}_m t_s,$$

where dBD represents a measured dry bulk density (g. cm^{-3}) calculated and averaged for each studied sample, after drying at 40°C in an air oven; TOC_m , represents the mean TOC value (wt. %) measured and averaged for each studied sample, and t_s , represents the sediment thickness (10 cm in this case). Bulk dry density was measured with a sampling step similar to that used for OM analyses, and then values were then averaged for each core. We have also compared our bulk dry density with those given in equation 2 where TOC is expressed in mg. g^{-1} (modified from Avnimelech et al., 2001):

$$(2) \text{ dBD} = 1.776 - 0.363 \text{Log}_e (\text{TOC} * 10)$$

Average TOC values were assessed by considering the TOC from soils sampled in dry valleys (four profiles, either encrusted or cultivated), and in plateaus (two profiles in barren surfaces).

4. Results

4.1. Bulk organic matter geochemistry

Rock-Eval 6 parameters are provided according to depth (Fig. 3). Characterization of the OM origin and its degradation states are presented in the figure 4.

Low TOC values, ranging from 0.15 to 0.31 wt. %, characterize the studied soils, with the highest values observed for soils sampled on the plateaus. Other soil profiles such as M, MM, C, and CC contain low TOC, close to 0.15 wt. %. These very low values, close to the threshold value with this pyrolyzer and caused by low intensity RE6 signals, imply also a large range of values of HI and OI indices (S_2 , S_3 , HI, OI), making their reliable further use difficult (Lafargue *et al.*, 1998). Like TOC values, S_2 and S_3 values from these soils are notably low, ranging from 0.07 to 0.34 mg HC. g⁻¹ sample and 0.14 to 0.20 mg O₂ g⁻¹ sample, respectively. TpS₂ values, however, exhibit large variability, with values between 399°C and 631°C.

For sediments sampled in the TK1 core, high TOC values increase from the bottom (1.14 wt. % - 46 cm depth) to the top (10.07 wt. %). S_2 and S_3 parameters displayed the same previous trend with a steady increase toward the top of the core. S_2 and S_3 exhibited values ranging from 0.99 to 34.92 mg HC. g⁻¹ sample and 1.89 mg O₂ g⁻¹ sample to 14.77 mg O₂ g⁻¹ sample, respectively. Toward the top of the core, TpS₂ values slightly decreased from 478 to 471°C.

Within the BB2 core, the two units were also characterized by their different OM content and quality. The lower unit 1 was almost OM free, as TOC values were systematically lower than 0.13 wt. %. S_2 and S_3 were very weak, with values lower than 0.03 mg HC. g⁻¹ sediment and 0.75 mg O₂ g⁻¹ sediment, respectively, whereas TpS₂ values decreased from 502 to 456°C toward the upper unit 2. Unit 2 provided TOC values ranging from 1.21 to 3.06 wt. % without any trend correlating with depth. Samples richer in OM (at 21, 31 and 41 cm depth) also exhibited higher S_2 and S_3 , with values ranging from 1.69 et 6.00 mg HC g⁻¹ sediment and 2.32 et 6.28 mg O₂ g⁻¹ sediment, respectively. Toward the top of the core, TpS₂ values decreased from 456 to 442°C.

TOC measured in samples from the lower part (0.28 to 0.54 wt. %) of the BK-08-02 core, where there is an absence of lamina, were lower than those sampled in the upper laminated part of the core (between

0.69 to 0.78 wt. %). These lower TOC values were accompanied by lower S_2 (from 0.12 to 0.18 versus 0.52 to 0.62 mgHC.g⁻¹ sediment in lamina) and also by lower S_3 values (2.91 to 3.06 versus 3.91 to 4.25 mg O₂ g⁻¹ sediment in lamina). As a consequence, organic matter in the lamina was more hydrogenated and less oxidized than that preserved in the non-laminated counterpart. TpS₂ values are highly variable and generally lower for lamina (404-440°C versus 390°C-509°C for non-laminated sediment).

4.2. Organic petrography

Palynofacies data are presented according to surface particles (Fig. 3) and percent of particles in the total assemblage.

The palynofacies assemblage in the TK1 core was dominated by aquatic OM (58 to 86 %) consisting of BrAOM (29 to 80%) and GP (5 to 36 %). In contrast with BrAOM, GP tended to decrease toward the surface, where their contribution reached 16 to 36 % in the deepest part but was only 5 to 9 % between 1-31 cm. The terrestrial contribution consisted of OP (3 to 28 %) and translucent to degraded LC (<1 to 19 %) with a minor TAOM contribution of < 3%. With the exception of the surficial sample (1 cm depth), OP decreased toward the surface to the benefit of LC particles. These latter particles were not observed in the last centimeters of the core (41 and 46 cm).

The palynofacies assemblage of the unit 1 BB2 core was mainly composed of particulate OM from the catchment (85 to 98 %). Of these terrestrial OM, OP (61 to 85 %) was the main class observed followed by LC debris enriched in DLC (11 to 22 %) and rare TAOM (maximum of 7 % at 141 cm). Only LC debris showed a trend with depth with an increase upward. Except for the deepest sample containing 4 % of BrAOM, GP was the observed class of aquatic particles that accounted for 2 – 13 % of the total assemblage. Within unit 2, terrestrial particles prevailed in the palynofacies assemblage (25 to 78%) and were apportioned between OP (9 to 43 %), LC debris (10 to 32 %) and, particularly, the degraded counterparts (5 to 31 %) and TAOM not exceeding 5 %. With the exception of the two first surficial samples, OP particles decreased upward from 43% at 61 cm depth to 8 % at 21 cm depth. TLC particles did not exceed 5 % (at 11 cm depth) and increased toward the surface, in contrast with DLC (from 31 %

at 61 cm depth to 5 % at 11 cm depth). Aquatic particles consisted of BrAOM, with their contribution reaching a high of 69 % at 21 cm and dropping below 20 % at 61 cm depth. Some GD particles were also found and contributed to 2 % at the unit base and reached 13% at the top of the core.

5. Discussion.

5.1. Soil organic matter

With TOC values ranging between 0.15 to 0.31 wt. %, the soils in this study were poor in organic matter. Nevertheless, such TOC values are consistent with those of various ferruginous Sahelian soils (Tab. 1). These low TOC values can be explained by the absence of litter due to vegetation cover and by the sandy texture of soils, particularly those located in dry valleys (4 profiles, holding the lower TOC values). SOM bearing this OC is likely derived from woody products or carbohydrates, as evidenced by their HI/OI ratio, which is always lower than 1/2 and is accompanied by high TpS₂ (Fig. 3, 4; Carrie et al., 2012, Sebag et al., 2006a).

5.2. Sources of organic matter in Sahelian lakes

Sedimentary OM in the TK1 core contains a significant aquatic contribution (Fig. 2, 3, 4). In addition, in the upper part of this core (0-36 cm), the HI/OI ratio is higher than 2 (fig. 4, 5a, b), corroborating the aquatic origin of this OM, which was most likely obtained from chlorophyll (Carrie et al., 2012). In contrast, the two deepest samples had an HI/OI ratio close to or lower than 1, providing evidence of ligno-cellulosic, carbohydrate or even protein origins of sedimentary OM (Carrie et al., 2012). Accordingly, the aquatic contribution diminishes or is less preserved than its terrestrial counterpart with depth as attested to by the relationship between the HI/OI ratios and those of the aquatic / terrestrial particles from palynofacies (Fig. 5a). This observed progressive decline might be explained by a higher predisposition of aquatic OM to earlier diagenetic processes (e.g., bacterial consumption, oxidation, cf. Meyers, 1997). Nonetheless, the two deepest samples from this core have the same signature as those observed in unit 2

of the BB2 core, characterized by a notably low HI/OI ratio and an aquatic / terrestrial particles ratio similar to those measured for the TK1 samples (Fig. 5a). Two hypotheses can be merged to explain the distribution of HI/OI ratios: (i) severe oxidation of OM, affecting both aquatic and terrestrial OM, as there is no change in palynofacies ratio or (ii) a local change in the source of sedimentary OM. Additional information can be revealed comparing RE6 ratio with the degraded (OP + TAOM) / preserved (TLC+DLC) terrestrial particles ratio (Fig. 5b). Origin of the low HI/OI ratio for these two samples can be explained by a severe degradation of the preserved terrestrial particles. Indeed, TK1 samples are well distributed along a straight line and are not affected by a change in the source of sedimentary OM (Fig. 5b). Earlier diagenesis could explain the distribution of TK1 samples in figures 5a, b and had first to affect the aquatic OM by a gelification process (Fig. 3) and, later, the fresh terrestrial particles, as observed previously in Lake Annecy (Noël et al., 2001). Because the OI values exhibit no significant changes with depth (Fig. 4), OM processes would be maintained in an oxygen-free or poorly oxygenated environment and are certainly imputable to microorganisms. This oxygen-depleted environment is frequently promoted by a fine sedimentation (Mayer, 1994) as seen in this core, explaining the high TOC content.

Unit 1 of the BB2 core is depleted in OM (TOC max. = 0.13 wt. %) and the little OM present consists of OP whose origin could be severe oxidation of ligno-cellulosic debris (Tyson, 1995). These values should be considered with caution due to the low TOC values; this strong oxidation is also expressed by very high OI values and low to very low HI values (Fig. 4). This significant contribution of terrestrial particles to the OM assemblage (Fig. 5a) for which a large part is altered (Fig. 5b), can easily explain the two indices from RE6 pyrolysis. Several options might explain the geochemical and optical signatures seen in the unit 1. Ligno-cellulosic debris could originate from a paleosol, which may exist prior to the establishment of this lake, and containing harshly altered OM because the oxidation degree of sedimentary OM from this unit is higher than that of the studied soils (Fig. 4). This soil could have been temporarily flooded, as evidenced by the occurrence of aquatic particles (Fig. 3, 5a). Other possibility would be that unit 1 corresponds to a filling of the lake fed by extremely altered terrestrial OM from the

catchment and by coarse detrital sediments or that the preservation of highly degraded OM particles comes from a severe impact of earlier diagenesis that affected the more hydrogenated OM particles. According to the particulate OM assemblage (Fig. 3), the RE6 pyrolysis indices, the HI/OI ratio (Fig. 4) and the palynofacies ratio (Fig. 5a), sedimentary OM from unit 2 would correspond to a mélange of terrestrial and aquatic OM. However, if the palynofacies ratio is close to those calculated for the TK1 samples with a lower HI/OI ratio, the aquatic or terrestrial contribution of sedimentary OM from unit 2 is more degraded than its counterpart from TK1 (Fig. 5a). This difference in degradation could be explained by the organic constituents of unit 2 in comparison with OM assemblage from TK1: GD particles are dominant, and BrAOM is rather scarce for the aquatic particles (Fig. 3), while the OP contribution is significantly higher for the terrestrial particles (Fig. 3), explaining the distribution of samples in figure 5b. Two non-exclusive alternatives may be considered to explain the contribution of such particles in this unit and hence their degree of oxidation. First, OM originating from deep soil might constitute a significant portion of the terrestrial source of OM due to erosion occurring along the shorelines, as there is no observed drainage network. Second, a strong diagenetic processes occurring earlier in unit 2 might also be promoted by coarser sedimentological particles (more silty than the TK1 core). This second possibility would easily explain why TLC particles, which are more sensitive to degradation than DLC particles, never exceed 5% in this unit. Contrary to the unit 1 base, the significant proportion of aquatic particles and the best preservation of OM observed in unit 2 provide reasonable evidence that the limit of these two units corresponds with the permanent impoundment of Lake Bangou Bi. As seen in section 2.3, this permanent lake would be dated earlier 1960s (Abdourhame Touré, 2011).

The source of sedimentary OM in the BK-08-02 core can only be inferred with the pseudo Van Krevelen diagram (Fig. 4). By comparing with the OM from the two other cores, it is realistic to draw the same conclusions given for unit 1 of the BB2 core (Fig. 4). Accordingly, the OM is highly degraded, remains essentially terrestrial or was subjected to a severe earlier diagenesis.

Studying sedimentary OM from these three lakes can increase understanding of the functioning of Sahelian lakes. Lake Tankalawal may be an excellent example of a permanent lake in which organic

sedimentation is ruled by significant aquatic production promoted by meso to eutrophic conditions. Within the sediment, earlier diagenesis provokes a continuous degradation of the labile constituents of aquatic OM and therefore a relative enrichment in resistant OM. In addition, below a certain depth (46 cm), this degradation also affects the labile terrestrial constituents, while the aquatic OM that is still preserved remains more resistant (Fig. 5b). Lake Bangou Bi reflects two distinct contexts. Unit 1 might correspond to a soil located in a depression occasionally flooded (supply of aquatic OM) and in which harshly degraded terrestrial OM from soil erosion is deposited with coarse sedimentological particles. Unit 2 corresponds to sediment deposition in a permanent lake in which a substantial aquatic contribution is mixed with terrestrial OM from shore erosion. Lake Bangou Kirey can be considered as a permanent lake where the essential OM is terrestrial and comes from a catchment that is highly dissected by gullies. A coupling between poorly mineralized waters due to the neighboring soils and strong degradation due to earlier diagenesis may explain the low aquatic productivity and low level of aquatic OM preservation within sediments.

5.3 Sahelian lakes as an unexpected organic carbon sink?

This study proposes a first estimate of the OC stocks by considering a thickness of 10 cm of core to compare these stocks with those from neighboring studied soils. In addition, mean OC accumulation rates were estimated for these Sahelian lakes (Bangou Bi and Bangou Kirey).

5.3.1 OC stocks in Sahelian soils and lacustrine environments

For soils from dry valleys (four profiles, either encrusted or cultivated), an apparent dry bulk density of 1.6 g cm^{-3} (Rajot, pers. data) and an average TOC value of 0.15 wt. % were calculated, providing a mean SOC stock of 0.24 kg C m^{-2} . For the two profiles sampled in the plateaus covered by tiger brush, an apparent dry bulk density of 1.3 g cm^{-3} (Volkoff et al., 1999) and an average TOC value of 0.24 wt. % were calculated, providing a mean SOC stock of 0.31 kg C m^{-2} . The calculated stocks for the first 10 cm

of topsoil (table 1) are in agreement with literature for the Sahelian belt (Buerkert and Lamers, 1999; Batjes, 2001; Fofana *et al.*, 2008). Weak top SOC stocks can be easily explained by a deficient vegetation cover density exacerbated by anthropogenic pressure (e.g., overgrazing and deforestation, Batjes, 2001) leading to a low level of litter production and a potential increase in soil erosion (e.g., Rajot *et al.*, 2001). Lastly, as shown in table 1, sandy and well-drained soils, such as arenosols, are frequently depleted in SOC (e.g., Feller and Beare, 1997; Saiz *et al.*, 2012).

For the lakes, the mean TOC value for TK1 samples (0-60 cm depth) reached 4.62 wt. %, and the mean TOC value for unit 2 of the BB2 core (0-65 cm depth) was 2.18 wt. %. For the BK-08-02 core, the occurrence of laminae between 0-120 cm depths testifies to a continuous sedimentation means that the beginning of a permanent impoundment of the lake is recorded in sediment and corresponds to 120 cm depth (Abdourhamane Touré, 2011). Therefore, a TOC value of 0.72 wt. % was calculated and corresponds to the average TOC measured for the three analyzed samples from the upper unit (0-120 cm). The average dry bulk densities measured and calculated (cf. eq. 2) are 0.75 / 0.68 g cm⁻³ (BB2), 0.43 / 0.45 g cm⁻³ (TK1) and 0.60 / 1.06 g cm⁻³ for BK-08-02. Accordingly, the mean OC stocks for 10 cm thickness are 1.6 / 1.5 kg C m⁻² (unit 2 from BB2), 2.0 / 2.1 kg C m⁻² (TK1) and 0.4 / 0.8 kg C m⁻² for BK-08-02. With the exception of the BK-08-02 core and with respect to uncertainties related to the calculation of these stocks, OC storage levels are 3 to 10 times higher than those estimated for the studied soils. The greater the detrital fraction input into the lakes, the lower the storage of OC in lacustrine sediments. Nonetheless, a part of SOC can be deposited in lacustrine sediments and can act as a new reservoir of SOC.

5.3.2. Accumulation rates of OC in Sahelian lakes

Based on the assumption that the establishment, and hence the sediment deposition, of the permanent Lake Bangou Bi, began in the 1960s (Abdourhamane Touré, 2011), a mean accumulation rate of OC could be assessed and corresponds to the limit between the two sedimentological units. If the average TOC value is 2.18 wt. % and the dry bulk density is 0.68 to 0.75 g cm⁻³, considering the thickness of unit

2 (65 cm), then the accumulation rate would be 193 to 213 g OC m⁻² yr⁻¹ for a recording time of 50 years. The same reasoning could be applied to the BK-08-02 core if we consider that the beginning of the sediment deposition occurs at the base of the upper laminated unit (i.e., 120 cm depth) and dates from the earlier 1960s, then the accumulation rate would be 104 to 183 g OC m⁻² yr⁻¹. With the exception of Lake Turkana, these rates would be higher than those in literature for other African lakes (Tab. 2). Nevertheless, such rates are of the same order of magnitude as those calculated for ponds or artificial reservoirs devoted to aquaculture (see values and references in Table 2). Non-exclusive assumptions could be evoked the high accumulation rates estimated in these Sahelian lakes:

1- First, soil erosion affects cultivated areas that are regularly fed by manure or other fertilizers, delivering some nutrients to the water column (Leblanc et al., 2008). Combined with a high water temperature, these nutrients would favor good primary aquatic production - which is subsequently subjected to mineralization in the water column or in sediment, as observed for the studied lakes - a major parameter governing the OC accumulation in sediments (Hedges and Keil, 1995). This finding would explain why the estimated rates are higher than those for aquaculture reservoirs.

2- Sahelian catchments frequently consist of sandy and erodible soils and can be aggravated by anthropogenic activities (i.e., culture and pasture, Leblanc et al., 2008; Cappelaere et al., 2009). This high level of detritus might explain why sediment accumulation is also high, a parameter which could promote the OC preservation in sediments (Hedges and Keil, 1995).

However, caution should be paid regarding our estimate, as the OC accumulation rate is based only on 50 years, which is a very short time compared to other natural lakes listed in table 2. Yet, an increase in the investigation timescale necessarily involves recording some environmental changes, either climatic (drought) or anthropogenic (reforestation, river management), acting as a negative feedback for sediments and OC accumulation rates. In addition, table 2 gathers a panel of values provided by different studies with different approaches (e.g., measurements versus modeling) with different uncertainties for estimating these rates. The differences in uncertainty factors need to be considered when comparing our rates with those from the literature.

7. Conclusions

The main originalities of this work are (i) the distinction of OM sources (aquatic versus terrestrial) preserved in Sahelian lacustrine sediments and (ii) a pioneering assessment of the ability of such lakes to store OC. If further studies provide additional evidence of OC storage within Sahelian lakes, it will be reasonable to conclude that these new lacustrine environments can act as a carbon sink at a regional scale. For these three lakes, OM sources, their contribution and preservation within lacustrine sediments and the related TOC contents of sediments are highly dependent on (i) physical and chemical conditions prevailing in the water column, (ii) sediment particle sizes and (iii) the importance of the detrital input from the shore or from the catchments. For the latter parameter, following a conventional rule, the greater the input of detrital material to the lakes, the lower the storage, and preservation of OC will be in lacustrine sediments. In addition, OM characterization has helped to define - and confirm - the sedimentological limit of the settling of the permanent Lake Bangou Bi (unit 2).

This study presents the first assessment of OC stock and related accumulation rates with a perspective on OC storage in studied soils. SOC stocks are commonly low in the abundant literature, but those estimated for these Sahelian lakes are surprisingly high, and OC accumulation rates are close to rates for ponds or reservoirs devoted to aquaculture. Clearly, these preliminary results have to be verified by other similar studies on a large set of representative lakes disseminated in the Sahelian belt. The results from such regional studies could subsequently be used to re-estimate regional OC budgets and stocks in this environment, which is highly sensitive to global change.

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figures captions

Figure 1. Geographic context of the studied site and samples location.

Figure 2. Main organic particles observed in BB2 and TK1 cores. Palynofacies classification derives from the review of Sebag et al. (2006c).

Figure 3. Rock-Eval 6 parameters and palynofacies evolution with depth for the BB2 and TK1 cores. S_3+S_3' correspond respectively to the release of CO₂ and CO during pyrolysis stage. Unit 1 from BB2 core is depleted in OC content (relevance threshold for TOC = 0.15 wt. %); however S_2 , S_3+S_3' and TpS_2 are given for information only (for the BB2 core, no particle counting was made at 51 cm depth since there is no sufficient quantity of sample. The core BK-08-02 is not shown in this figure because of data limitations).

Figure 4. Pseudo Van-Krevelen diagram of soil and lacustrines sediments samples. With reference to the Van Krevelen diagram (i.e. $(H/C)_{at.}$ vs $(O/C)_{at.}$), this diagram provides a rapid evaluation of origin of organic matter and its degraded stage defined by an increase in OI and a decrease in HI values respectively. Doted lines correspond respectively to the HI/OI ratio delimiting the main organic constituents (see Carrie et al., 2012 for further details).

Figure 5. (a): HI/OI (or $S_2 / (S_3+S_3')$) plotted with the palynofacies ratio between aquatic OM particles (BrAOM + GP) and terrestrial OM particles (OP + TAOM + (TLC + DLC, i.e. ligno-cellulosic debris)). (b): HI/OI (or $S_2/(S_3+S_3')$) versus a palynofacies ratio between preserved terrestrial OM particles (TLC+DLC) and degraded terrestrial OM particles (OP + TAOM). Signification of symbols is referred to figure 4 and number corresponds to the depth.

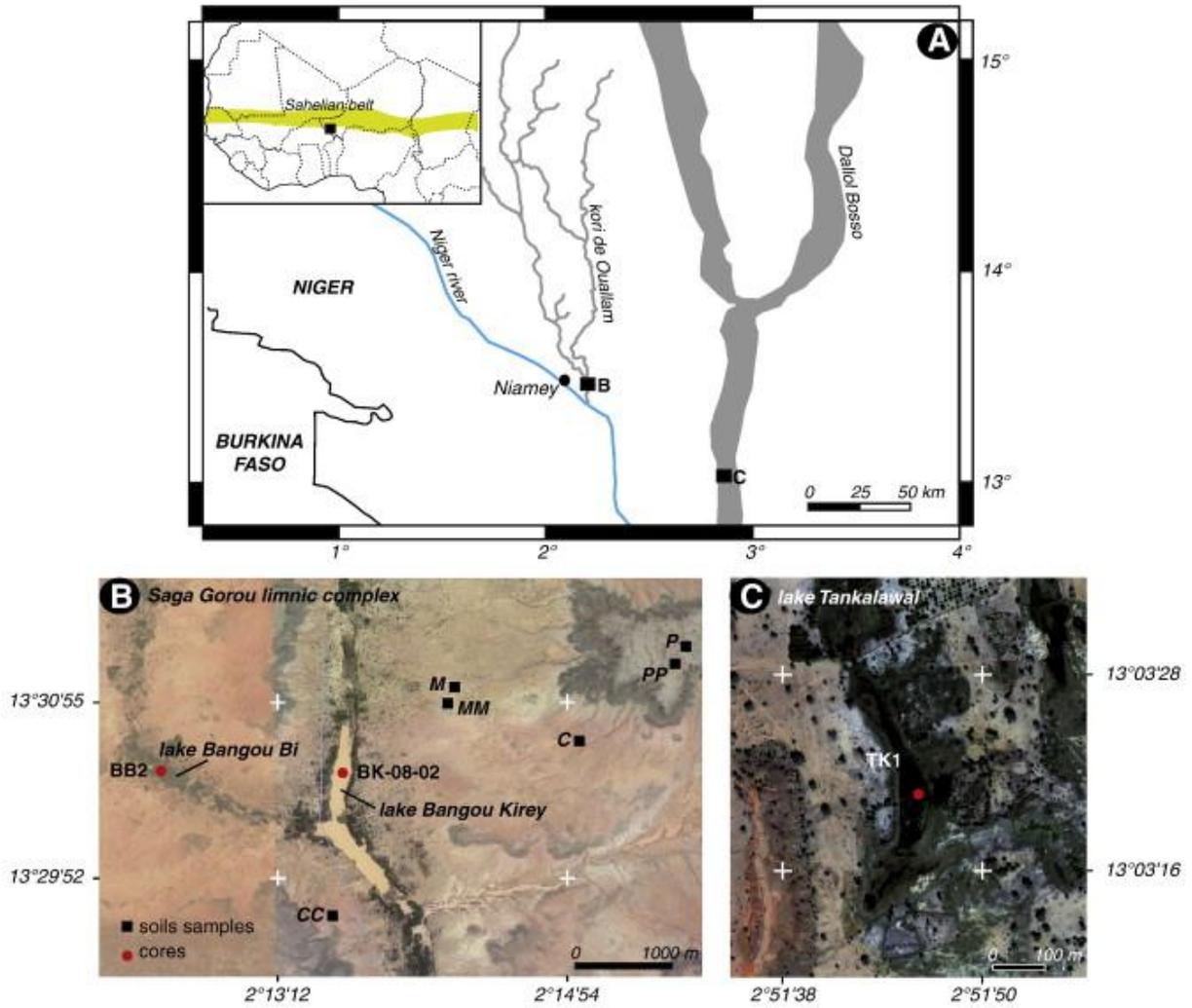


Fig. 1. : Geographic context of the studied site and samples location.

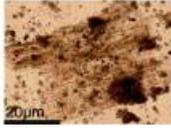
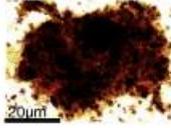
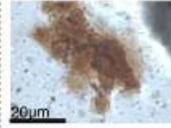
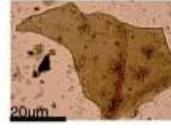
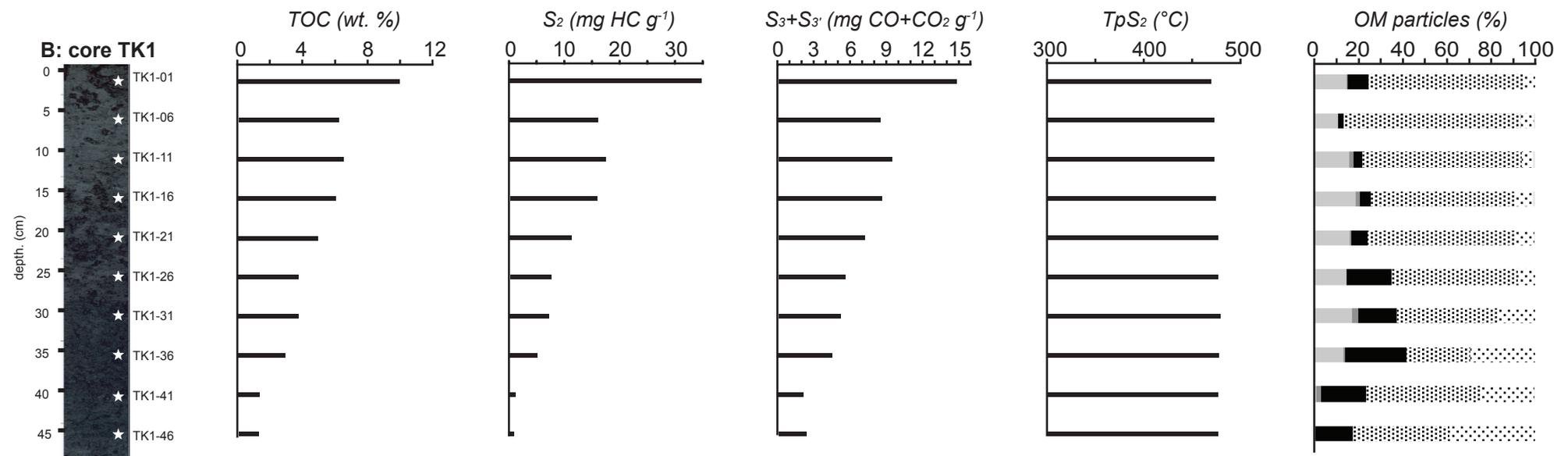
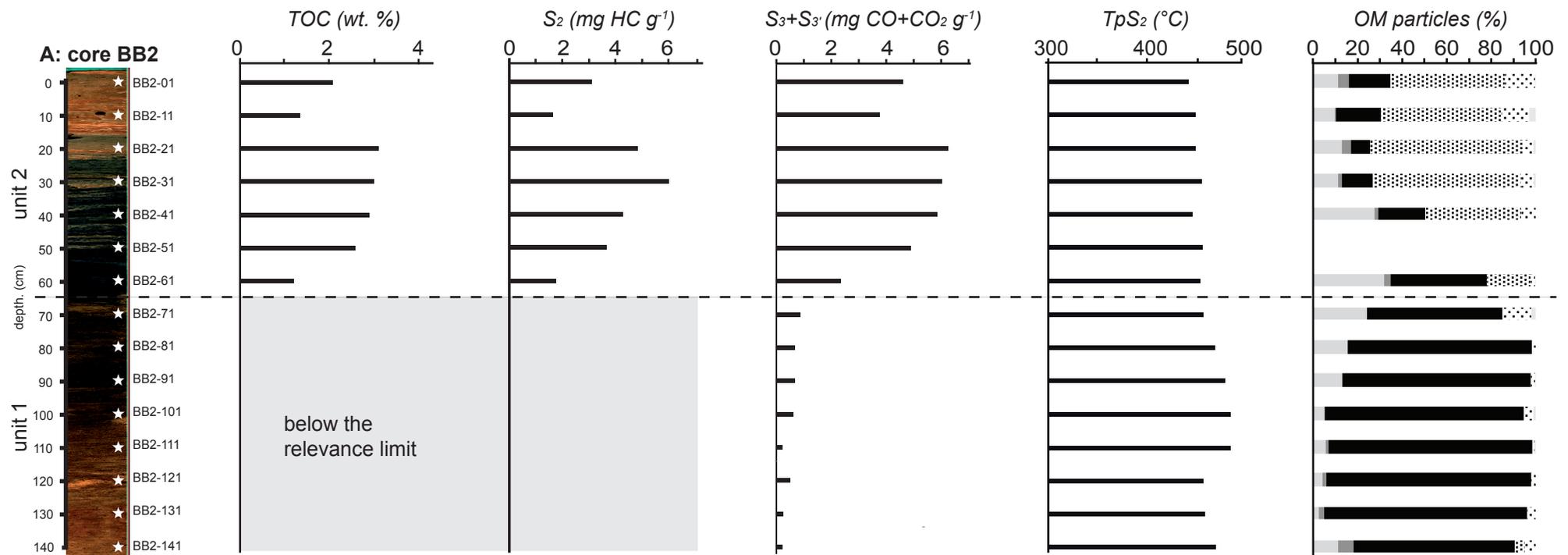
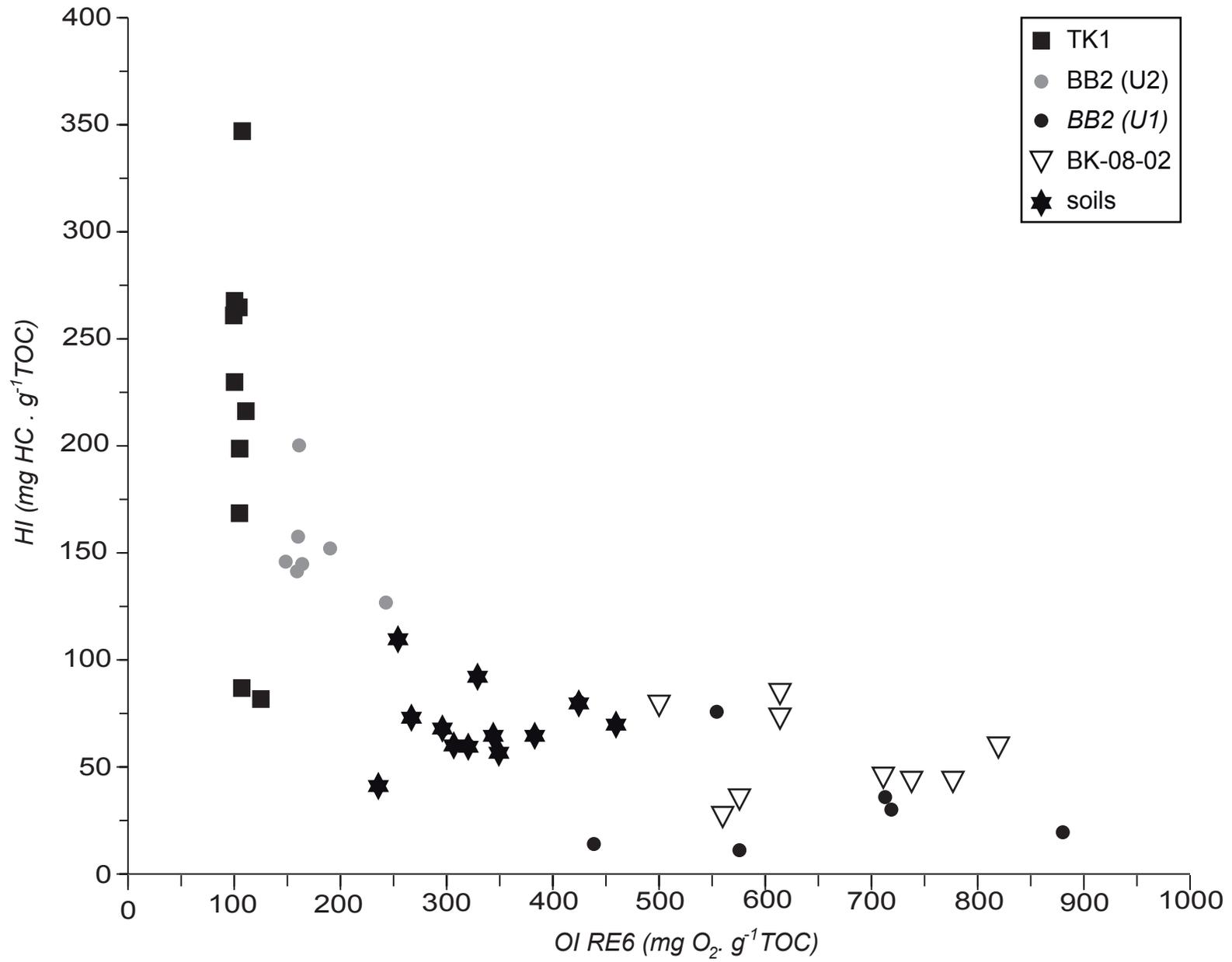
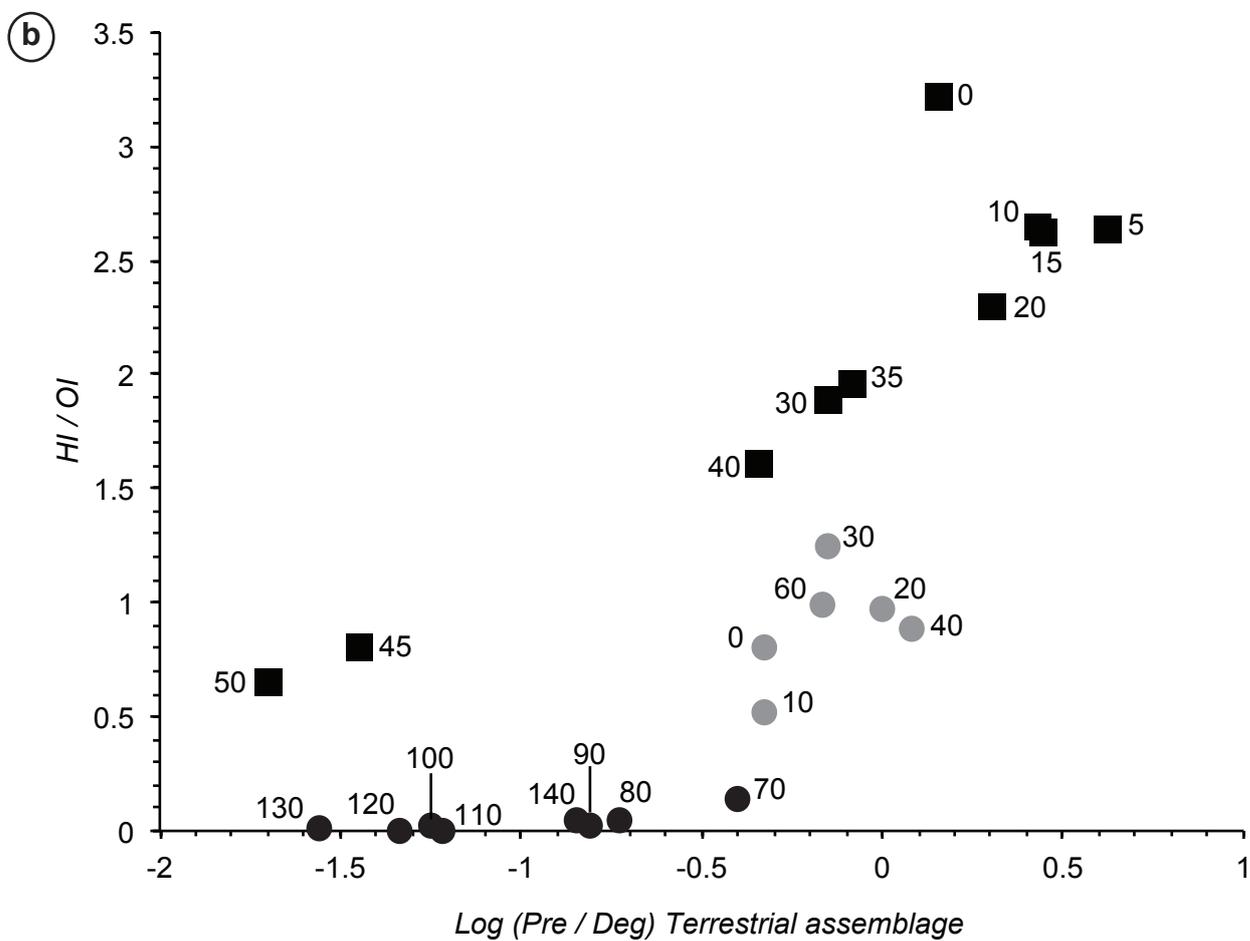
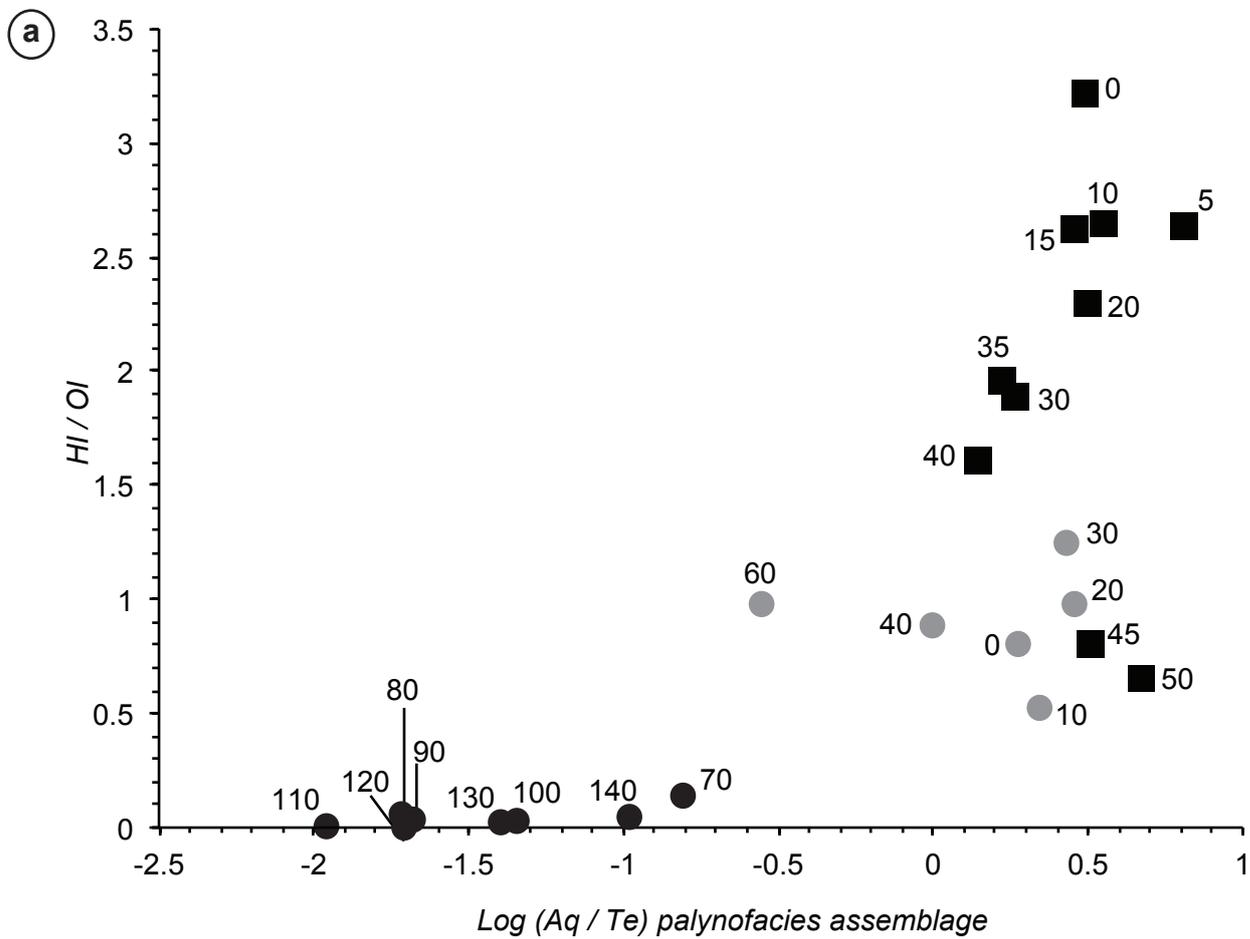
	translucent ligno-cellulosic debris (TLC)	degraded ligno-cellulosic debris (DLC)	reddish & black amorphous organic matter (TAOM)	Opaque particles (OP)	brown amorphous organic matter (BrAOM)	gelified particles (GP)
						
Description	observable vascular structures	degradation of vascular structures	diffuse edge with black inclusions	fully opaque	diffuse edge	orange gel like material
Origin	higher plants	higher plants	higher plant (deep soil layers)	higher plant highly oxidised	submerged higher plant	cell luminae products of roots
	<i>terrestrial environment</i>				<i>aquatic environment</i>	

Fig. 2. : Main organic particles observed in BB2 and TK1 cores. Palynofacies classification derives from the review of Sebag et al. (2006c)







Soils Taxonomy	Land Cover/land Use	Country	topsoil OrgC (0-0.1m) (kg C m ⁻²)	References
various	various	Western Africa	1.10 – 1.20	Batjes, 2001
Cambic Arenosols	cultivated surfaces (millet), encrusted soils	Niger	0.26	this study
Cambic arenosol	sparse savanna	Northern Sudan	0.15 - 0.25	Farage <i>et al.</i> , 2007
Cambic Arenosols	fallow	Senegal	0.20	Batjes, 2001
Skeletal Leptosols	tiger bush	Niger	0.31	this study
Psamentic Paleustalfs	cultivated surfaces (millet)	Niger	0.24-0.26	Fofana <i>et al.</i> , 2008
Psamentic Paleustalfs	cultivated surfaces (millet)	Niger	0.25	Buerkert and Lamers, 1999
Lixisols	traditional parkland agroforestry, improved agroforestry, degraded land	Mali	0.55	Takimoto <i>et al.</i> , 2009
nc	Savanna	Senegal	0.37 - 0.50	Ringius, 2002
Orthithionic Gleysols	cultivated surfaces (rice)	Senegal	1.39	Haefele <i>et al.</i> , 2004
Eutric Vertisols	cultivated surfaces (rice)	Senegal	1.03	Haefele <i>et al.</i> , 2004
Arenosols	open wood savanna	Senegal	0.38 - 0.73	Elberling <i>et al.</i> , 2003
Arenosols	grass savanna	Senegal	0.41	Elberling <i>et al.</i> , 2003
Arenosols / Regosols	grassland/isolated shrubs	Senegal	0.29	Woomer <i>et al.</i> , 2004
Arenosols / Regosols	grassland/scattered shrubs	Senegal	0.41	Woomer <i>et al.</i> , 2004
Arenosols / Regosols	shrubby grassland	Senegal	0.63	Woomer <i>et al.</i> , 2004
Arenosols / Regosols	degraded grassland	Senegal	0.29	Woomer <i>et al.</i> , 2004
nc (sandy soils)	various cultivated surfaces from Old Peanut basin	Senegal	0.19 to 1.39	Tschakert <i>et al.</i> , 2004
Arenosols to Calcisols	Senegal Peanut basin, G. Senegalenis & P. Reticulum	Senegal	0.40 – 0. 60	Lufafa <i>et al.</i> , 2008
Acrisols, Lixisol	Savanna	Northern	1.10 to 1.30	Volkoff <i>et al.</i> ,

and Luvisols nc	farmed parkland	Benin Northern Nigeria	0.65 to 0.72	1999 Farage et al., 2007
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Table 1: OC Stocks in various Sahelian soils for 0.0- 0.1m depth. In *italic*, values are given according our density measurements of Millet cultivated area (Fofana et al., 2008); values of SOC content are initially given between 0-0.05m for Elberling et al., 2003. For numerous studies SOC contents, initially given for 0.0-0.2 or 0.3m, were arbitrary divided by 2 or 3, even if a strong variability in SOC content with topsoil occurs, in particular when soils are finely covered by cyanobacteria (e.g. Malam-Issa et al., 2001). 80% of the SOC stock in western African soils is stored in the upper 0.0 – 0.3m (Batjes, 2001).

Lakes / ponds	OC accumulation rate (g m ⁻² yr ⁻¹)	Time scale investigated (yr)	References
<i>Sahelian belt</i>			
Bangou Bi and Kirey (Niger)	104-213	50	This study
Chad	19	Holocene	Einsele <i>et al.</i> , 2001
<i>rift valley and great Lakes</i>			
Sonachi	9	175	Verschuren, 1999
Naivasha	12-62	186	Stoof-Leichsenring <i>et al.</i> 2011
Turkana	162	few hundreds	Barton and Torgersen 1988
Victoria	16	Holocene	Einsele <i>et al.</i> 2001
Kivu	11	50	Pasche <i>et al.</i> 2010
Tanganyika	9	2000-2500	Einsele <i>et al.</i> 2001
Malawi	16	Holocene	Einsele <i>et al.</i> 2001
<i>other tropical lakes</i>			
Kariba	23	<50	Kunz <i>et al.</i> 2011
African tropical lakes	1-45	< 25 000	Giresse <i>et al.</i> , 2010
lakes from Cameroon	9-56	nc	Giresse <i>et al.</i> 1994
Taypi Chakakkota (Andes)	10	Holocene	Abbot <i>et al.</i> 1997
lakes from Brazil	7-41	500	Turcq <i>et al.</i> 2002
<i>reservoirs, ponds</i>			
World reservoirs	400	nc	Dean and Gorham 1998
aquaculture ponds	28-333	2-52	Boyd <i>et al.</i> 2010
Nasser-Nubia (Egypt-Sudan)	260	1700	Mullholland and Elwood, 1982
Agriculturally-eutrophic impoundments (Iowa, USA)	148-17392	100	Downing <i>et al.</i> 2008

Table 2: OC accumulation rates in various African and South American lakes. Sediments retained by dams for agricultural purposes are also given. For lake Kivu, the mean value is an average between white and brown layers (0-43cm depth). Lake Nasser-Nubia is considered as an agriculturally reservoirs. Kariba is an artificial lake along the river Zambezi. OC accumulation rate for lake Turkana was assessed with the equation (1).