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δ^{13}C variation of soil organic matter as an indicator of vegetation change during the Holocene in central Cameroon

Variation du δ^{13}C de la matière organique des sols comme marqueur des changements de végétation au cours de l'Holocène au centre du Cameroun

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ABSTRACT

In order to better understand the dynamics of the forest–savanna mosaic from central Cameroon, we analyzed ^{13}C and ^{14}C profiles of six oxisols: two under forests and four under savannas. The δ^{13}C soil profiles collected in the forests indicate that these environments are stable at least since the mid-Holocene, whereas the areas currently covered by savannas were formerly occupied by more forested vegetations. The ^{14}C dating of organic matter indicate that the late extension of the savannas in central Cameroon date from the Late Holocene, starting from 4000–3500 ^{14}C yr BP.

RÉSUMÉ

Afin de mieux comprendre la dynamique de la mosaïque forêt–savane du centre du Cameroun, nous avons analysé les profils isotopiques ^{13}C et ^{14}C de six oxisols: deux sous forêt et quatre sous savane. Les profils de δ^{13}C des sols sous forêts indiquent la permanence de ce couvert végétal depuis au moins le milieu de l'Holocène, alors que les sols couverts actuellement par de la savane étaient auparavant occupés par une végétation plus boisée. La datation ^{14}C de la matière organique montre que l'extension des savanes du centre du Cameroun date de l'Holocène supérieur et n'a débuté que vers 4000–3500 ^{14}C an BP.

1. Introduction

In Equatorial Africa, the edge of the evergreen forest massif consists of a mosaic of semi-deciduous forests

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and savannas. Savannas also occur within the forest massif in small patches but also, as in the Bateke plateaus in Congo, over wide areas. The origins of these open landscapes, which occur under present-day equatorial climate mostly suitable for forest presence, are still a matter of debate (Bayon et al., 2012). Isotope analyses on soil organic matter are widely used to discriminate between C3 (mostly forests) and C4 (mostly savannas) vegetation through δ^{13}C measurements and thus are powerful tools to reconstruct the history of these former landscapes (Boutton, 1996). Although based on a few sites, the soil profiles from Congo (Schwartz, 1997; Schwartz et al., 1992) and Gabon (Delègue et al., 2001) recorded large-scale environmental changes in relation with the Late Quaternary climatic succession in specific areas of the Atlantic Coast and the Bateke Plateaus.

As soon as the late fifties, Bachelier et al. (1957) studied soils from the savanna–forest mosaic from the lowlands of central Cameroon. They concluded that the anthropogenic activities and mainly repeated burnings were responsible for the recent opening up of the forest. However, Youta Happi (1998) and Guillet et al. (2001) showed that the forest has been currently expanding since, at least, the last decades.

In this article, we present isotope analyses on six soil profiles recovered in central Cameroon along a south-north transect from Abong Mbang to the southeast (3°50′N–13°20′E) and Ngambe Tikar to the north-west (5°40′N–11°40′E), in an area where the lack of lacustrine or swamp deposits hampers our understanding of past environmental changes. The goal of our study is to discuss the changes in forest extents during the recent past, particularly at the age of the Late Holocene forest crisis evidenced throughout central Africa (Vincens et al., 1999). These changes are thought to have strongly influenced the local populations (Bayon et al., 2012; Verdu et al., 2009).

2. Materials and methods

2.1. Soil profile location

Two soil profiles were taken in semi-deciduous Sterculiaceae/Ulmaceae forests (at Abong Mbang and Ngambe Tikar) and four profiles were taken in savannas (at Ndjolé, Sangbé, Maboen, and Nditam) (Fig. 1). The savannas are of Guineo-Congolian phytogeographical type (White, 1983) and are characterized by tall grasses, mainly *Hyparrhenia* sp. with shrubs and trees. (*Lophira lanceolata, Annona senegalensis, Bridelia ferruginea, Bauhinia thonningii, Terminalia* sp.). All the studied soils were located in the highest part of the relief, and classified as oxisols, with texture varying from clayey to sandy-loamy.

2.2. Soil sampling

Soils were sampled using a 6-cm-diameter auger, to a depth of 390 cm, at 10-cm intervals between the surface and 50 cm, and at 20-cm intervals from 50 cm to the bottom. The soil samples were air-dried, sieved with a 2-mm mesh, homogenized and ground to $< 200\ \mu$m. The forest and savanna core sites were chosen in low declivity zones, within undisturbed vegetation apart from the present savanna–forest boundary.

2.3. Stable isotope analyses

Since C3 plants (the dominant plants in forests) and C4 plants (the dominant plants in savannas) are isotopically distinct, it is possible to detect shifts from tropical forests to grasslands (or vice versa) from the δ^{13}C signature of organic matter in soils (Desjardins et al., 1996; Mariotti, 1991; Runge, 2002; Sanaiotti et al., 2002; Schwartz et al., 1996).

The isotopic ratio ($R = {}^{13}C/{}^{12}C$) is reported in standard delta notation (δ^{13}C), defined as parts per thousand (‰)

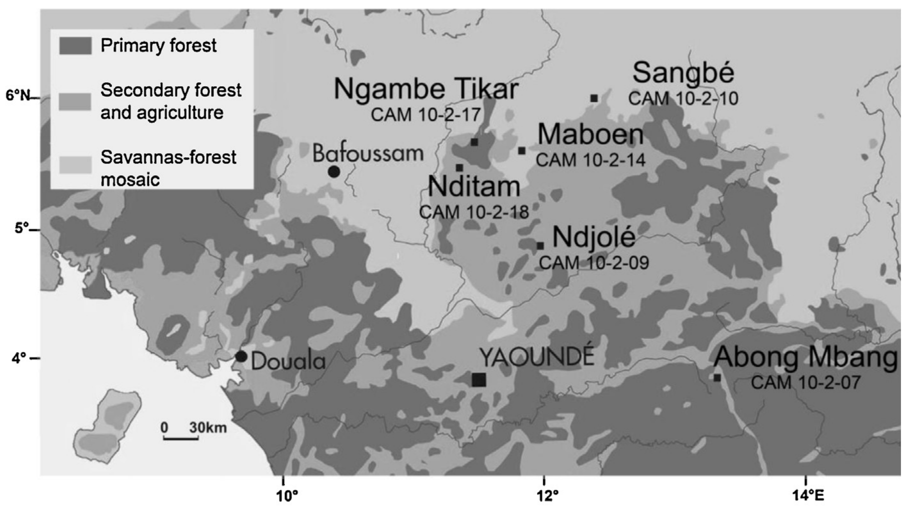

Fig. 1. Location map of the study sites. The simplified vegetation map is from Guillaumet et al. (2009).

Fig. 1. Carte de localisation des sites étudiés. La carte de végétation simplifiée est reprise de Guillaumet et al. (2009).

deviation from a standard (Vienna Pee Dee Belemnite) (Peterson and Fry, 1987):

$$\delta^{13}C = [(R_{sample}/R_{standard}) - 1] \times 1000$$

The samples were air-dried and sieved at 2 mm. Aliquots of these samples were ground at 70 meshes and submitted to an acid attack by HCl 10%. The samples were combusted in an elemental analyzer (Costech) for carbon content analysis. $\delta^{13}C$ was measured on a continuous-flow gas-ratio mass spectrometer (Finnigan Delta PlusXL) coupled with the elemental analyzer. Standardization is based on acetanilide for elemental concentration, NBS-22 and USGS-24 for $\delta^{13}C$. Precision is better than $\pm$ 0.10‰ for $\delta^{13}C$, based on repeated internal standards.

2.4. Radiocarbon dating

The radiocarbon measurements performed on the bulk soil organic matter represent a mixture of younger and older carbon pools whose residence time is increasing with depth and consequently do not correspond to the absolute age of soil organic matter (Guillet et al., 2001; Schwartz et al., 1996). As a consequence, the temporal resolution of past vegetation changes is low and must be interpreted with caution (Boutton et al., 1998; Trumbore et al., 1995; Wiedemeier et al., 2012). In addition, the calibration of ^{14}C ages does not make sense for soil samples. For an easier comparison with earlier studies, ^{14}C values are expressed in ^{14}C yr BP (apparent age according to Guillet et al., 2001). AMS ^{14}C measurements were performed on bulk soil organic matter samples with a 3 MV Pelletron (NEC, Middleton, Wisconsin, USA). The sample pre-treatment was the same as for the other analysis.

3. Results

3.1. Total organic carbon content

The six studied profiles showed a relatively similar distribution of organic carbon with depth (Fig. 2). In the surface (0–10 cm) layer, the organic carbon (C) content ranges from 18.8 to 27.9 mg·g^{-1}. Then, the C content decreases abruptly until the 60–70-cm level, without evidence of any organic paleohorizon: at this depth, the C content ranges from 4.7 to 10.3 mg·g^{-1}. Below this level, the C content decreases slightly to reach 1.6 to 4.1 mg·g^{-1} at 380–390-cm depth.

3.2. Depth variability in $\delta^{13}C$ values of soil organic matter

Soil profiles from semi-deciduous forests (Fig. 3) show a typical $\delta^{13}C$ pattern with values ranging from –28.4 to –26.9‰ at the surface, an increase of about 2‰ in the subsurface levels between 10 and 30 cm, and then a slight increase until values ranging from −23 to −25.4‰ between 200 and 390 cm.

$\delta^{13}C$ values range from a minimum of −16.4 to a maximum of −13.9‰ in the surface layer from the savanna sites (Ndjolé, Sangbé, Maboen, Nditam). An increase of 1.4 to 1.6‰ is observed at the uppermost decimeters, with a maximum recorded at 20–30 or 30–40 cm (Fig. 3). Downward, a pronounced decrease is recorded, with $\delta^{13}C$ values falling to −19.1 and −17.6‰ at 120–130 cm. Two of these profiles record a stabilization of the ^{13}C values between 120–130 cm and 380–390 cm (at Sangbé, between −17.6 and 19.8‰, and at Maboen, between −17.2 and −18.2‰), while in the two other sites (Ndjolé and Nditam), the $\delta^{13}C$ values decrease progressively until −21.9 and −22.3‰ at 360–370 cm.

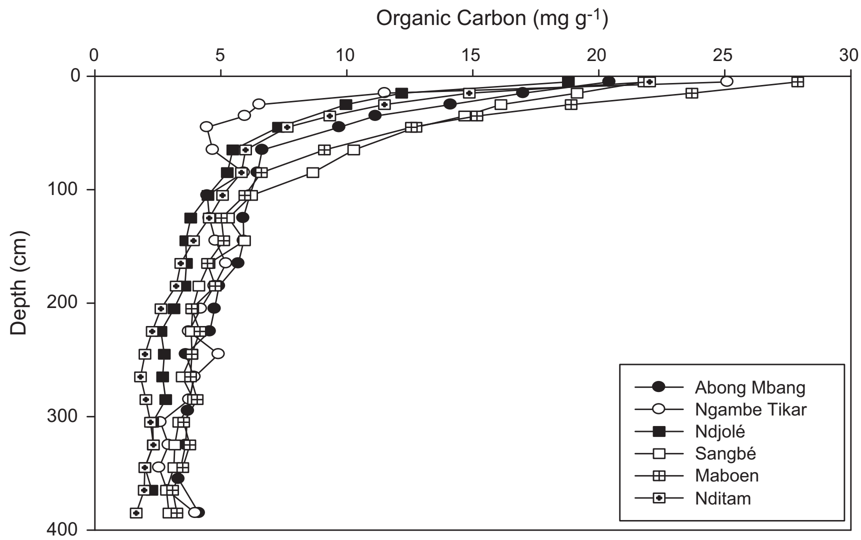

Fig. 2. Variation with depth of the total carbon content for the six studied soil profiles (circles represent forest profiles and squares represent savanna profiles).

Fig. 2. Variation de la teneur en carbone total en fonction de la profondeur pour les six profils de sol étudiés (les cercles représentent les profils de forêt et les carrés les profils de savane).

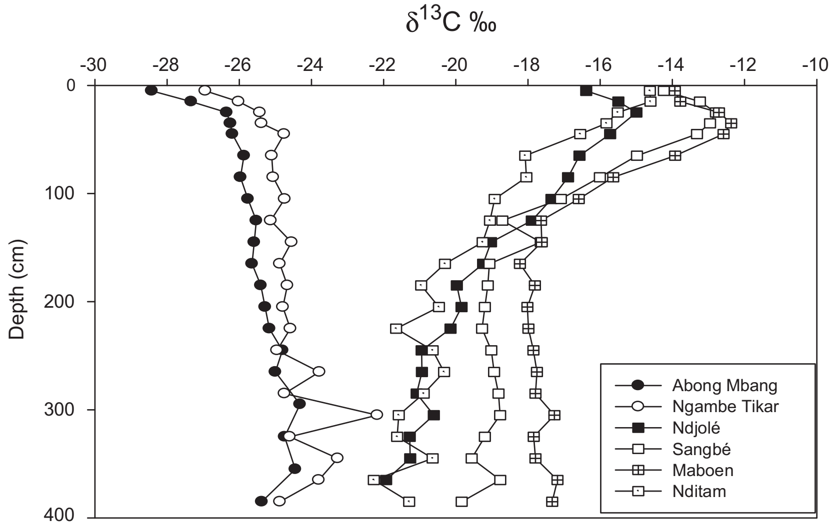

Fig. 3. Variation of $\delta^{13}C$ values with depth in the studied soil profiles (circles represent forest profiles and squares represent savanna profiles).

Fig. 3. Variation du $\delta^{13}C$ en fonction de la profondeur dans les profils étudiés (les cercles représentent les profils de forêt et les carrés les profils de savane).

3.3. ^{14}C dating of soil organic matter

As the incorporation of carbon fixed from the atmosphere since atomic weapons testing in the early 1960s, which nearly doubled the amount of ^{14}C in the atmosphere, high values of radiocarbon (> 100% of the modern carbon) are generally found in the surface soil layers. No dating of surface layers was realized. However, even at the 20–30-cm level, three profiles show a modern ^{14}C signature and the three other ages vary between 180 and 485 ^{14}C yr B.P (Table 1). Below this level, the radiocarbon ages increase downward at different rates: at 400-cm depth, Abong Mbang and Ndjolé profiles record radiocarbon ages of 3900–4050 ^{14}C yr BP, whereas ages from the other profiles are older and range from 5900 to 7000 ^{14}C yr BP. There is no differentiation between the forest and savanna profiles.

4. Discussion

As far as the total carbon content is concerned, no significant difference is observed between the forest and savanna soils. Our results show similar carbon content and distribution compared to other African oxisols with clayey or median texture (Brunet et al., 2007). Total carbon decreases in an exponential manner (Bennema, 1974).

Desjardins et al. (1991), Martinelli et al. (1996), Gouveia et al. (1997) and Pessenda et al. (1998) among others have already observed that the $\delta^{13}C$ of soil organic matter increases with depth in forest profiles. It is accepted that a 3.5–4.0‰ isotopic enrichment is due to mineralization and humification decomposition processes (Desjardins et al., 1996; Mariotti and Petershmitt, 1994; Martinelli et al., 1996). The $\delta^{13}C$ values observed in the forest soil profiles of Abong Mbang and Ngambe Tikar lie within the range of

Table 1
^{14}C of soil organic matter in the six soil profiles expressed as a percentage of modern carbon (pMC) and conventional radiocarbon age in years (non-calibrated).

Tableau 1
^{14}C de la matière organique du sol dans les six profils, exprimé en pourcentage de carbone moderne (pMC) et en âge radiocarbone conventionnel en années (non calibré).

	Abong Mbang CAM-10-2-07 Forest 3°49′52,6″N 13°19′53,9″E		Ngambe Tikar CAM-10-2-17 Forest 5°39′01,6″N 11°28′58,0″E		Ndjolé CAM-10-2-09 Savanna 4°51′09,4″N 11°58′35,9″E		Sangbé CAM-10-2-10 Savanna 5°59′16,3″N 12°23′35,0″E		Maboen CAM-10-2-14 Savanna 5°35′04,8″N 11°50′25,7″E		Nditam CAM-10-2-18 Savanna 5°27′06,1″N 11°22′06,8″E	
Depth (cm)	pMC	Radiocarbon age BP	pMC	Radiocarbon age BP	pMC	Radiocarbon age BP	pMC	Radiocarbon age BP	pMC	Radiocarbon age BP	pMC	Radiocarbon age BP
20–30	94.16	485	97.80	180	100.30	Modern	101.17	Modern	10.14	Modern	94.88	420
80–90	84.12	1390	85.20	1285	83.70	1430	84.09	1390	73.06	2520	78.61	1935
160–170	75.52	2255	77.21	2080	75.54	2255	65.71	3375	56.80	4540	63.44	3655
260–270	64.47	3525	46.33*	6180*	–	–	57.66	4425	46.40	6165	48.63	5790
380–390	60.56	4030	45.44	6335	61.49**	3905**	47.78	5930	42.18	6935	44.16	6565

* 280–290 cm.
** 360–370 cm.

expected values for soils where C3 plants have remained the dominant vegetation cover over time. Similar values have been recorded by Schwartz et al. (1992) and Guillet et al. (2000, 2001) in stable forests from Central Africa.

The $\delta^{13}C$ values measured in the upper layers of the savanna profiles are typical of C4-dominated vegetation. They closely match values from savannas already encountered in Gabon, Congo and Cameroon by Delègue et al. (2001), Schwartz et al. (1992), Schwartz (1997) and Guillet et al. (2001) (−12 to −17‰). At these later sites, the $\delta^{13}C$ values changed from −22 to −24‰ between 2 m and 4 m depth, reflecting, according to the authors, the presence of an organic matter inherited from former C3-dominated vegetation. In our savanna profiles of Ndjolé and Nditam, quite similar $\delta^{13}C$ trends are observed, with values reaching from −21 to −22‰ at the bottom of the profiles. Although these values are slightly less negative than those observed by Delègue et al. (2001), Schwartz et al. (1992), and Schwartz (1997), they likely reflect dominant C3 vegetation. The savanna sites of Sangbé and Maboen show a strong decrease in $\delta^{13}C$ values between 30 and 130 cm. However, the $\delta^{13}C$ values stabilize downward, around −18 to −20‰ and −17 to −18‰, respectively, which testify the former presence of mixed vegetation with C3 plants and C4 plants. These intermediate $\delta^{13}C$ values are not reported in the literature and, to our knowledge, no corresponding vegetation landscape exists in central Africa today, except at a single site, located at the forest–savanna boundary at Kandara (Guillet et al., 2001). Schwartz (1991) and Guillet et al. (2001), also suggested, based on almost similar $\delta^{13}C$ values, the presence of a savanna more densely forested than today. Similar ^{13}C values from −19.7 to −20.5‰ were also recorded between 0 and 2 m depth in the southeastern region of Brazil, on a native Cerrado vegetation site (Wilcke and Lilienfein, 2004). This Cerrado is grassland with up to 40% cover of 3 to 5 m tall trees.

Another interpretation of such $\delta^{13}C$ values has been proposed by Schwartz (1991): they could represent an average $\delta^{13}C$ from different vegetation types, which have succeeded over time in relation with paleoclimatic fluctuations.

The age distribution of the analyzed organic matter is not significantly different from those reported in central Atlantic Africa. In Gabon, Delègue et al. (2001) mentioned a mean age of 4200 ^{14}C yr BP at 180 cm. In Cameroon, Guillet et al. (2001) mentioned a mean age of 2640 and 4855 ^{14}C yr BP at 200 cm and Schwartz et al. (1992) mentioned ages slightly older: 6960 ^{14}C yr BP at 200 cm and 8300 ^{14}C yr BP cm at 300 cm in Congo.

Because of the heterochrony of the soil organic matter, these mean ages do not indicate directly the age of vegetation changes. However, they give an indication of the timing of such changes (Sanaiotti et al., 2002). Based on our ^{14}C data, we can deduce that the extension of savannas in central Cameroon did not begin before the Late Holocene (ca 4000–3500 ^{14}C yr BP). This is in agreement with pollen studies, which record the collapse of the forest massif from 3300 to 2400 cal yr BP (Lézine et al., 2013 this volume and reference therein). Further north in the Adamaoua region, Vincens et al. (2010) showed that the semi-deciduous forest begun to decline earlier at 6000 cal BP.

At Ndjolé and Nditam, the $\delta^{13}C$ profiles indicate that the former vegetation was a forest of semi-deciduous type, which was present at the Early to Middle Holocene. Differently, at this time, the isotopic values at Sangbé and Maboen show a more complex landscape formed by a mixture of C3 and C4 plants.

5. Conclusion

We obtained for the first time Holocene paleoenvironmental data in the savanna–forest mosaic zone of central Cameroon. Our results indicate that this modern landscape is mostly inherited from the last environmental crisis, which led to a widespread forest collapse in the Atlantic Equatorial Africa at the end of the African Humid Period 4000–3500 years ago. A stable environment is recorded in the present-day forests of Ngambe Tikar and Abong Mbang. The savannas soil profiles display a more complicated picture with $\delta^{13}C$ values pointing to specific environmental conditions which are not known today: either densely forested grasslands or an alternation of successive savanna–forests phases at the sample sites. More profiles are required to understand better this history.

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