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Past tree cover of the Congo Basin recovered by phytoliths and $\delta^{13}C$ along soil profiles

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ABSTRACT

The tropical moist forests (TMF) of the Congo Basin are extremely diverse in terms of structure and functional diversity. Previous paleoecological work suggests that these forests have experienced dramatic changes over the last millennia, related to climate or humans. These disturbances still influence today's repartition of forests and savannas as well as species distributions. The objective of this study is to explore the sensitivity of phytolith assemblages, compared to the $\delta^{13}C$ of soil organic carbon (SOC), to reconstruct past tree cover of the present TMF.

Large transects across different geological substrata and forest communities were explored. In total, 18 soil profiles were investigated for pedogenic features, and 53 radiocarbon dates from SOC and charcoals were obtained. Phytolith extractions from modern soils and along four soil profiles were performed. The $\delta^{13}C$ of SOC and phytolith assemblages were interpreted in terms of tree cover changes. One of the most interesting results highlighted by this study was the strong match between phytolith tree cover and the $\delta^{13}C$ signal; as it not only aids the interpretation of $\delta^{13}C$ soil signals, but also puts into question the transport behavior of phytoliths in soil by processes that are still poorly understood.

The $\delta^{13}C$ SOC method has been successfully used to study major vegetation changes in Africa, but has never been previously constrained with another proxy of tree cover. This study confirms the value of a multi-proxy approach to investigate past vegetation changes in African tropical moist forests, and shows that SOC $\delta^{13}C$ and phytolith signatures in soil profiles display the same dynamics and are complementary. They suggest that the majority of the present forested sites never experienced a true savanna phase.

1. Introduction

Biogeographical patterns of plant distribution in the tropical moist forests of the Congo Basin are currently linked to environmental conditions, specifically rainfall (Poorter et al., 2004), or soil and geological substrate (Réjou-Méchain et al., 2008; Fayolle et al., 2012). However, large parts of the modern distribution still remain poorly explained, and it has been suggested that recent past changes in climate may explain discontinuities in species composition across Africa. Also, Schwartz (1992) suggested that enclosed savannas were more extensive two or three thousand years ago, and that opening the forest would have facilitated the Bantu migration from north to south of the forest block. Later, Maley (2002) suggested that a major general and synchronous forest destruction occurred between 3000 and 2500 years BP, by considering pollen records from Lake Barombi Mbo (Maley and Brenac, 1998), Lake Ossa (Reynaud-Farrera et al., 1996) in west Cameroon, and lakes in the Congo (Elenga et al., 1994, 1996; Vincens et al., 1999); as well as the present distribution of two light-demanding pioneer trees abundant in the periphery and gaps of the rain forest: oil palm (*Elaeis guineensis*) and Okoumé (*Aucoumea klaineana*). This event, later called the 'third millennium BP crisis of the central African rainforest' was well recorded in several swamps and lakes from Atlantic Central Africa (Ngomanda et al., 2009b). However, given the spatial distribution of these records, extrapolation across the entire Congo Basin would be problematic. Also, several studies support the opinion that it was not a general deforestation event of the Inner Congo Basin, but the development of a mosaic of mature and secondary forests of pioneer trees (Neumann et al., 2012a, 2012b) due to an intensification in seasonality. In another recent study, Thiéblemont et al. (2013) suggests that most of the surface of Gabon and western Congo were free of forest from c. 4000 to 2000 BP. However, this

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argument is unconvincing, as it is in complete disagreement with regional paleocological studies (Maley et al., 2014). In order to test the hypothesis of extensive forest destruction between 3000 and 2500 BP and the spread of large patches of savanna formations, this study aims to identify past savanna traces in the Congo Basin, particularly along the Sangha River, a probable past savanna corridor (Maley and Willis, 2010).

Lake sediments, susceptible to recording these past vegetation changes, in the center of the Congo Basin are almost nonexistent. Only a few sediment records from swamp forests (swampy depressions and forest hollows) in the lowland forest of the northwest Republic of Congo have been published (Brncic et al., 2007, 2009; Tovar et al., 2014), but none have recorded a major event between 3000 and 2500 BP. At the base of the Mopo Bay sequence (2600–2400 BP) in northern Congo (Brncic et al., 2009), the sediment contained high percentages (36%) of Poaceae pollen; the presence of forest cover was also confirmed by the dominance of tree pollen. Later, Maley and Willis (2010) interpreted this pollen assemblage as a short savanna extension.

Though much less indicative than lake sediments, because of the difficulty to establish age-depth chronology and the lack of preservation of many microfossils commonly used as paleoecological proxies (e.g. pollens), soil profiles were used as alternative archives to estimate the past tree cover dynamic during the last thousand years around the Congo Basin (Schwartz et al., 1986; Delègue et al., 2001; Desjardins et al., 2013; Pietsch and Gautam, 2013). These studies related variations in the abundance of ^{13}C in soil organic matter along soil profiles, enabling the history of the forest-savanna successions to be reconstructed; indeed, this type of photosynthesis mainly determines the natural abundance of ^{13}C in plants. The $\delta^{13}C$ signature of C_3 plants (trees, shrubs, herbs and grasses of closed habitats) are comprised between −33‰ and −24‰, whereas that of C_4 plants (mostly Poaceae and Cyperaceae from open tropical habitats) are comprised between −16‰ and −10‰. These different signatures, of the vegetation growing in the soil, are then recorded in the underlying profile, which permits the history of former vegetation to be estimated (Boutton, 1996).

As no soil profiles were previously studied from the center of the Congo Basin, a large transect across different geological substrata and forest communities was explored. In this study, more than 18 soil profiles were investigated for pedogenic features. Field observations, charcoal presence, C content and the carbon isotope composition ($\delta^{13}C$) of soil organic carbon (SOC) were measured, and numerous radiocarbon dates from SOC and charcoals were obtained (Morin-Rivat et al., 2014; Bentaleb et al., 2015).

However, interpretation of $\delta^{13}C$ from SOC along the soil profiles becomes hazardous when intermediate values between the C_3 and C_4 pools are recorded. This can be due to either mineralization and humification decomposition processes (Mariotti and Peterschmitt, 1994; Wynn et al., 2005), or to a mix of organic matter derived from C_3 and C_4 plants. Four soil profiles with different $\delta^{13}C$-detph patterns were selected from the initial 18 and analyzed for their fossil phytolith content. The starting assumptions were that if C_4 grass savanna occurred in the past, grass silica short cell phytoliths would have been incorporated into the soil; and if phytolith transport along the profile was comparable to the SOC, it would be possible to precisely record the $\delta^{13}C$. Hardly any studies have tried to combine phytoliths and $\delta^{13}C$ in tropical soils (Alexandre et al., 1999; Calegari et al., 2013; Coe et al., 2014; Ribeiro Rocha Augustin et al., 2015), and never in Africa. This study examines the reliability of the association of $\delta^{13}C$ values and phytolith records to interpret past forest-savanna successions, and discusses the savanna extension during the third millennium BP crisis of the central African rainforest.

2. Materials and methods

2.1. Study area and sampling

The study area corresponds to the CoForChange project (http://www.coforchange.eu/fr/) in the forests of the so-called "Sangha River Interval" region that includes parts of Cameroon, Central African Republic and the Republic of Congo (Fig. 1). One wooded savanna and several different types of lowland forests were sampled: dense forests with stands of Owom (*Manilkara mabokeensis*), Ayous (*Triplochiton scleroxylon*), Limbali (*Gilbertiodendron dewevrei*), and a sparse tree canopy forest with an understorey dominated by giant herbs, principally from the family Marantaceae. All sites were located on hilltops, and samples from approximately one hundred grams of soil were collected every 10 cm along the profiles, from the top to the base (usually 150 cm). Subsequently, subsamples were performed at different intervals to conduct several analyses.

2.2. Radiocarbon dating and stable isotope analyses

In total, 52 AMS radiocarbon dates were obtained from soil organic matter and charcoals along the 18 profiles. The AMS dating was performed at Poznan Laboratory for Radiometric Dating and by the ARTEMIS Radiocarbon Laboratory Facility (LMC14, Saclay France).

The charcoals were gently dry cleaned to remove soil organic matter before AMS dating. The samples of soil organic matter were sieved and acid washed before AMS dating.

The ^{14}C dates obtained from the charcoals and soil organic matter were not calibrated: bulk SOC represents a mixture of young and old carbon pools whose residence time increases with depth, and do not correspond to the absolute age (Schwartz et al., 1996; Guillet et al., 2001; Wiedemeier et al., 2011). However, because numerous previous studies presented calibrated SOC ages, the charcoals and SOC ages were calibrated using the southern hemisphere calibration SHCal13 (Hogg et al., 2013), and graphically drawn with Bacon software (Blaauw and Christen, 2011) for potential comparisons.

The carbon isotopic composition of the soil profiles, expressed as $\delta^{13}C$ values, were obtained from dried and ground soil samples using an acid wash treatment with HCl (0.6 N) to remove carbonates. Carbon isotope values were measured by dry combustion (1200 °C) using a Delta V Advantage isotopic ratio mass spectrometer (IRMS) coupled with a Flash EA 1112 (Thermo Scientific, laboratory of LIENS, La Rochelle), and the Optima Isotope Ratio Mass Spectrometer Optima coupled with a Euro Vector 3000 Elemental Analyzer (ISEM laboratory, Montpellier). The $\delta^{13}C$ values are expressed in δ notation relative to V-PDB belemnite. The precision is better than 0.3‰.

2.3. Soil texture analysis

Samples were analyzed at the Water, Soil, and Plant Analysis laboratory of Cirad, Montpellier (France). Soil texture (clay, sand, and silt fractions) was determined using the pipette method (Gee and Bauder, 1986). The soil textures are expressed as a percent of the different fractions: clay (<2 μm), clay loam (2–20 μm), silty loam (20–50 μm), fine sand (50–200 μm), and coarse sand (200–2000 μm).