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Short Paper

Ancient charcoal as a natural archive for paleofire regime and vegetation change in the Mayumbe, Democratic Republic of the Congo

Wannes Hubau [a,b,*], Jan Van den Bulcke [a], Peter Kitin [b], Florias Mees [c], Geert Baert [d], Dirk Verschuren [e], Laurent Nsenga [a,b], Joris Van Acker [a], Hans Beeckman [b]

[a] Ghent University, Department of Forest and Water Management, Laboratory for Wood Technology, Coupure Links 653, B-9000 Gent, Belgium
[b] Royal Museum for Central Africa, Laboratory for Wood Biology, Leuvensesteenweg 13, B-3080 Tervuren, Belgium
[c] Royal Museum for Central Africa, Department of Geology and Mineralogy, Leuvensesteenweg 13, B-3080 Tervuren, Belgium
[d] University College Ghent, Department of Plant Production, Schoonmeersstraat 52, B-9000 Gent, Belgium
[e] Ghent University, Department of Biology, Limnology Unit, K.L. Ledeganckstraat 35, B-9000 Gent, Belgium

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ABSTRACT

Charcoal was sampled in four soil profiles at the Mayumbe forest boundary (DRC). Five fire events were recorded and 44 charcoal types were identified. One stratified profile yielded charcoal assemblages around 530 cal yr BP and >43.5 cal ka BP in age. The oldest assemblage precedes the period of recorded anthropogenic burning, illustrating occasional long-term absence of fire but also natural wildfire occurrences within tropical rainforest. No other charcoal assemblages older than 2500 cal yr BP were recorded, perhaps due to bioturbation and colluvial reworking. The recorded paleofires were possibly associated with short-lived climate anomalies. Progressively dry climatic conditions since ca. 4000 cal yr BP onward did not promote paleofire occurrence until increasing seasonality affected vegetation at the end of the third millennium BP, as illustrated by a fire occurring in mature rainforest that persisted until around 2050 cal yr BP. During a drought episode coinciding with the 'Medieval Climate Anomaly', mature rainforest was locally replaced by woodland savanna. Charcoal remains from pioneer forest indicate that fire hampered forest regeneration after climatic drought episodes. The presence of pottery shards and oil-palm endocarps associated with two relatively recent paleofires suggests that the effects of climate variability were amplified by human activities.

Introduction

Combined reconstruction of past climate variability and ecosystem dynamics increases our understanding of ecosystem response to current and future climate change (e.g., Willis and Birks, 2006). Substantial work in temperate and arid regions of the northern hemisphere contrasts with the significant knowledge gaps that continue to exist for many tropical regions, particularly Central Africa (e.g., Leal, 2001; Emery-Barbier and Thiébault, 2005; Tchouto et al., 2009; Théry-Parisot et al., 2010; Maley et al., 2012; Neumann et al., 2012b). A well-known concept in tropical paleoecology and biogeography is that of the Central African forest refuges, which are submountainous, fluviatile or coastal regions enjoying rather moist (micro-) climate conditions thought to protect rainforests during dry climate anomalies (Maley, 1996, 2004; Sosef, 1996; Maley and Brenac, 1998; Leal, 2001, 2004). Yet paleoecological reconstructions suggest that rainforest and other Central African ecosystems show a remarkably high sensitivity to natural climate changes such as prolonged drought or increased seasonality (e.g., Maley, 1996, 2001, 2004; Ngomanda et al., 2007, 2009a,b). Also, human activity cannot be overlooked when discussing climate and vegetation changes during the last three millennia, when agriculture and iron smelting were introduced in Central Africa, even though before the last millennium human impact on Central African forests was probably marginal (e.g., Maley, 1996, 2004; Brncic et al., 2007; Maley et al., 2012; Neumann et al., 2012b).

The most important source of evidence for the climate and vegetation history of Central Africa is lake-sediment records (e.g., Russell and Johnson, 2005, 2007; Stager et al., 2009) and the fossil pollen they contain (e.g., Maley, 1996, 2004; Maley and Brenac, 1998; Brncic et al., 2007; Hessler et al., 2010). These studies provide high-resolution temporal records from a select few locations with undisturbed lacustrine sedimentation, but do not offer great spatial detail. In contrast, macrocharcoal fragments can be found in terrestrial soils of any type of vegetation, reflecting local paleofire regimes. Also, the analysis of soil charcoal from profiles in natural environments (pedoanthracology) is not influenced by the effects of fuelwood selection strategies, as observed in charcoal analysis from archeological sites (archeoanthracology) (Di Pasquale et

* Corresponding author at: Ghent University, Department of Forest and Water Management, Laboratory for Wood Technology, Coupure Links 653, B-9000 Gent, Belgium. Tel.: +32 9 264 61 23; fax: +32 9 264 90 92.
E-mail addresses: wannes.hubau@ugent.be, w.hubau@leeds.ac.uk (W. Hubau), jan.vandenbulcke@ugent.be (J. Van den Bulcke), kitin@wisc.edu (P. Kitin), florias.mees@africamuseum.be (F. Mees), geert.baert@hogent.be (G. Baert), Dirk.verschuren@ugent.be (D. Verschuren), lnsenga@yahoo.fr (L. Nsenga), joris.vanacker@ugent.be (J. Van Acker), hans.beeckman@africamuseum.be (H. Beeckman).

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al., 2008; Théry-Parisot et al., 2010). Pedoanthracology has proven to be a useful tool for reconstructing Holocene paleofire regimes in natural environments, especially in the forest-boundary of submountainous regions (Carcaillet and Thinon, 1996; Carcaillet et al., 1997; Di Pasquale et al., 2008). Additionally, soil charcoal analysis can reveal the past presence of woody plant taxa that are only rarely detected in pollen assemblages (Elenga et al., 2000; Lebamba et al., 2009). As a result, pedoanthracology is highly complementary with palynology for reconstruction of past vegetation dynamics (Emery-Barbier and Thiébault, 2005; Théry-Parisot et al., 2010; Hubau et al., 2012).

Hitherto, only a handful of studies on soil charcoal in Central Africa included the identification of charred wood remains, due to the high species richness of the area and lack of a scientifically sound identification procedure (e.g., Schwartz et al., 1990; Hart et al., 1996). Recently, Hubau et al. (2012) developed a transparent identification protocol that can allow a taxonomically more precise identification than generally obtained by pollen analysis. The main objective of the present study is to contribute to knowledge of Central African paleofire and vegetation history by applying this protocol to soil charcoal assemblages from an area of the Congolese rainforest that is expected to be sensitive to climate change. We selected a non-archeological study site (the Luki Reserve) at the southern end of the Mayumbe hills in the Democratic Republic of the Congo, (DRC), which are thought to have served as a submountainous forest refuge during late Pleistocene and Holocene episodes of climate deterioration (e.g., Maley, 1996, 2004; Sosef, 1996). Dry or more seasonal climate conditions result in forest regression and fragmentation, particularly at forest boundaries. However, little is known about patterns of past forest fragmentation in Central Africa at the local scale (e.g., Tchouto et al., 2009) and about the role of fire, which even in tropical rainforests is one of the most important causes of forest destruction (Cochrane et al., 1999; Cochrane, 2003). Therefore, specific research questions for the present study are: (1) what was the temporal and spatial occurrences of fire in the southern Mayumbe? (2) How consistent are anthracological reconstructions with known paleoclimate history? (3) Were paleofires only caused by climatic anomalies or also by humans?

Material and methods

Study area

The Lower Guinean rainforest is separated from the West African rainforests by the Dahomey Gap in Togo and Benin and from the eastern part of the rainforest by the swamps of the Ubangi and Congo Rivers (Leal, 2004). The Mayumbe is a chain of forested hills stretching along the Atlantic Ocean from Gabon down to the Luki reserve, which is located in the Bas-Congo province of the DRC, between 05 45.00′S and 05 70.00′S and between 13 05.00′E and 13 30.00′E (Fig. 1). With the establishment of the Luki reserve in 1937, its forests, soils and possible charcoal archives have been safeguarded from intense anthropogenic disturbance. As part of the 'Man and Biosphere' (MAB) program of UNESCO, a tripartite conservation zonation was applied, including a fully protected 'central zone', which contains an important relict of the semi-evergreen subequatorial Guinean rainforest that once covered the entire Mayumbe hills (e.g., Donis, 1948; Lebrun and Gilbert, 1954). However, its position at the southernmost edge of the Mayumbe forest (Fig. 1A) makes this forest relict vulnerable to climate change, involving natural forest fragmentation. As such, the Luki reserve is highly suitable for paleobotanical research.

Charcoal sampling and profile description

Four pedoanthracological profiles were excavated in the Luki reserve (Fig. 1). One profile was located in the peripheral UH48 stand (Couralet, 2010; Hubau et al., 2012) and three in the central zone (CZ1, CZ2, CZ3) of mature rainforest (Fig. 1B). All profiles were only a few kilometers apart and located at elevations ranging from 180 to 460 m (Fig. 1D). Soil charcoal sampling was conducted as described by Hubau et al. (2012). For each profile a relatively flat area was chosen, avoiding steep slopes to minimize the effects of erosion or colluvial sedimentation (see Fig. 1D, including information on relief). Furthermore, all sampling sites were well-drained and located outside former agricultural fields (see Carcaillet and Thinon, 1996). Figure 1C presents a distribution map of soil types in the Luki reserve based on the soil map of Bas-Congo presented by Van Ranst et al. (2010).

Next, exploratory holes were drilled with an Edelmann auger, down to 1 m. A pedoanthracological profile of 100 cm × 150 cm surface area was excavated on a spot where prospection yielded charcoal and where the soil was relatively dry and penetrable. All profiles were excavated down to a depth of 140 cm. Deeper charcoal layers were detected and sampled by augering in the bottom of the profile pit. Charcoal fragments (largest dimension > 2 mm) were carefully collected by hand, and sorted per depth interval of 20 cm. Specific anthracomass was calculated as described by Carcaillet and Thinon (1996). Thin sections were prepared from undisturbed soil samples, following polyester impregnation using standard procedures (Murphy, 1986) and micromorphological features were described applying polarization microscopy, using the concepts and terminology of Stoops (2003). These features reveal variations in texture and possible bioturbation.

Charcoal description, identification and radiocarbon dating

For each profile interval, up to 50 charcoal fragments were analyzed using reflected light microscopy (RLM) following Hubau et al. (2012). All charcoal fragments were grouped into charcoal types, of which each type generally represents one species. Next, a large fragment of each charcoal type was mounted on a stub for scanning electron microscopy (SEM). Using SEM images, charcoal types were described applying the numbered anatomical features used for the on-line InsideWood database (IAWA Committee, 1989; InsideWood, 2011; Wheeler, 2011; Hubau et al., 2012). This produces two strings of numbered features. The first string represents primary features that are easily visible, while the second string represents secondary features that are variable or unclear. Finally, all charcoal types were identified applying the Central African identification protocol described by Hubau et al. (2012).

Soil features and distribution of charcoal types within the profile revealed possible profile stratification. One charcoal fragment from each stratigraphic interval was selected for AMS ^{14}C measurement at the Poznán Radiocarbon Laboratory (Poland) or Beta Analytic (Florida, USA). In case of ambiguous stratification patterns, two or three charcoal fragments from different intervals were selected. Calibration was performed with the OxCal v4.1.5 software (r:5) (Bronk Ramsey, 2009) using the SHCal04 calibration curve (McCormac et al., 2004).

Evaluation of identification reliability

The final result of the charcoal identification protocol is the association of each charcoal type with a small group of woody plant species, ranked according to their resemblance with the charcoal type anatomy (Hubau et al., 2012). Specifically, a 5-point ranking system was used, whereby 5 points were attributed in the case of perfect agreement between charcoal anatomy and woody species anatomy. Finally, the charcoal type received a 9-character label composed of the three first letters of respectively family, genus and species name of one of the best ranked species (Hubau et al., 2012). All identifications were evaluated according to two different reliability criteria. Criterion A concerns the phytosociological similarity of the retained species, with a good score if all highest ranked species have similar habitat preferences and a bad score if the highest ranked species occur in different vegetation types. Criterion B is based on the number of highest ranked species and their anatomy rank, with a high score for good resemblance between charcoal and