

Charcoal-inferred Holocene fire and vegetation history linked to drought periods in the Democratic Republic of Congo

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Abstract

The impact of Holocene drought events on the presumably stable Central African rainforest remains largely unexplored, in particular the significance of fire. High-quality sedimentary archives are scarce, and palynological records mostly integrate over large regional scales subject to different fire regimes. Here, we demonstrate a direct temporal link between Holocene droughts, palaeofire and vegetation change within present-day Central African rainforest, using records of identified charcoal fragments extracted from soil in the southern Mayumbe forest (Democratic Republic of Congo). We find three distinct periods of local palaeofire occurrence: 7.8–6.8 ka BP, 2.3–1.5 ka BP, 0.8 ka BP – present. These periods are linked to well-known Holocene drought anomalies: the 8.2 ka BP event, the 3rd millennium BP rainforest crisis and the Mediaeval Climate Anomaly. During and after these Holocene droughts, the Central African rainforest landscape was characterized by a fragmented pattern with fire-prone open patches. Some fires occurred during the drought anomalies although most fires seem to lag behind them, which suggests that the open patches remained fire-prone after the actual climate anomalies. Charcoal identifications indicate that mature rainforest patches did persist through the Early to Mid-Holocene climatic transition, the subsequent Holocene thermal optimum and the third millennium BP rainforest crisis, until 0.8 ka BP. However, disturbance and fragmentation were probably more prominent near the boundary of the southern Mayumbe forest. Furthermore, the dominance of pioneer and woodland savanna taxa in younger charcoal assemblages indicates that rainforest regeneration was hampered by increasingly severe drought conditions after 0.8 ka BP. These results support the notion of a dynamic forest ecosystem at multicentury time scales across the Central African rainforest.

Keywords: Central Africa, charcoal analysis, fire, palaeobotany, palaeoenvironment, vegetation history, wood anatomy

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Introduction

Central African Holocene forest dynamics were mostly reconstructed using palynological data from lake and swamp sediments (Maley & Brenac, 1998; Elenga *et al.*, 2004; Ngomanda *et al.*, 2007, 2009). Fragmentation of Central African rainforest into forest–savanna landscapes (Fig. 1) is considered as an important result of Holocene climate variability, with droughts as major events (Schwartz *et al.*, 1990; Maley & Brenac, 1998; Vincens *et al.*, 1998; Elenga *et al.*, 2004; Leal, 2004; Maley, 2004; Russell & Johnson, 2007; Ngomanda *et al.*, 2009; Neumann *et al.*, 2012a). Fire is regarded as one of the main natural causes of forest perturbation. Fires frequently burn forest edges near open vegetation

patches which are prone to desiccation (Laurance *et al.*, 2000; Cochrane, 2003; Broadbent *et al.*, 2008; Nelson *et al.*, 2012; Colombaroli *et al.*, 2014).

Little is known, however, on palaeofire occurrence in Central African rainforests although fires leave charcoal as an important palaeobotanical archive (Scott, 2000; Cochrane, 2003, 2003; Colombaroli *et al.*, 2014; Tovar *et al.*, 2014). Terrestrial charcoal archives are unique for tracing fires and the composition of burnt vegetation types, but they have hardly been explored in Central Africa. Therefore, this study deals with the question whether there could be a direct temporal link between Holocene drought, palaeofire and vegetation change within present-day Central African rainforest by comparing soil charcoal records with existing climate reconstructions.

Analysis of charcoal fragments from radiocarbon-dated stratified soil layers is highly complementary

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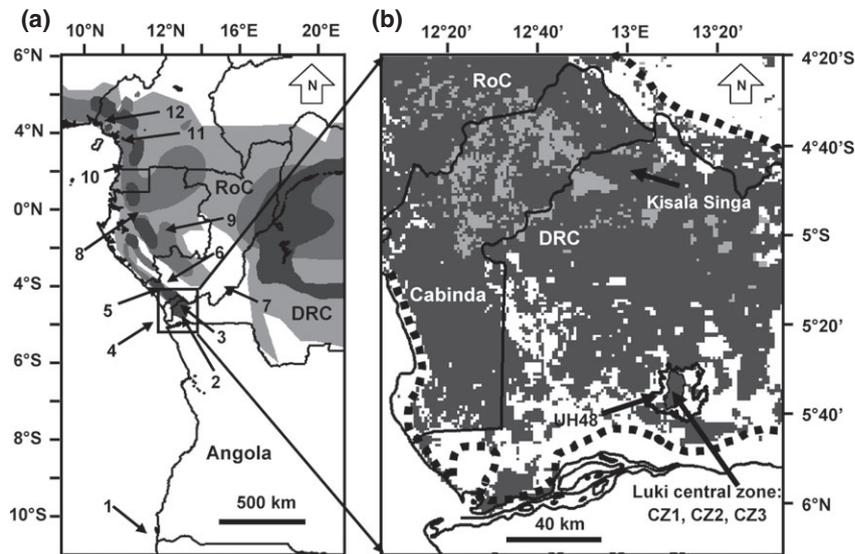


Fig. 1 Localization of the study area. (a) Late Pleistocene glacial rainforest refuges (dark grey) (Maley, 1996), Mature rainforest extent during the third millennium BP crisis (intermediate grey) (Maley, 2004) and current rainforest extent (light grey) (Mayaux *et al.*, 1997). Important study sites are indicated: 1 = marine core Geob 1023 (Kim *et al.*, 2002; Schefuß *et al.*, 2005), 2 = Luki reserve (Hubau *et al.*, 2013a); 3 = Kisala Singa forest (study site of this article); 4 = marine core Geob 6518 (Schefuß *et al.*, 2005; Bayon *et al.*, 2012), 5 = Lake Sinnda (Vincens *et al.*, 1998), 6 = lake Kitina (Elenga *et al.*, 2004), 7 = Ngamakala pond (Elenga *et al.*, 2004), 8 = lake Nguène (Ngomanda *et al.*, 2007, 2009), 9 = lake Kamalété (Ngomanda *et al.*, 2007), 10 = Nyabessan swamp (Ngomanda *et al.*, 2009), 11 = lake Ossa (Reynaud-Farrera *et al.*, 1996), 12 = lake Barombi-Mbo (Maley, 1996, 2004; Reynaud-Farrera *et al.*, 1996; Maley & Brenac, 1998). (b) Detail of current mature rainforest (dark grey) and regenerating forest (light grey) in the study area. Current forest cover is heavily fragmented especially due to human activities, while fragmentation during and after Holocene droughts was likely climate-driven.

with palynology and offers some unique advantages (Emery-Barbier & Thiébault, 2005; Théry-Parisot *et al.*, 2010; Hubau *et al.*, 2012). First of all, macrocharcoal fragments (>2 mm) are not subject to the problems of long-distance or species-specific transport which apply for pollen analysis. As such, charcoal archives provide local information concerning the zonal vegetation, whereas pollen inevitably mirror to some extent the special vegetation around water bodies. Secondly, charcoal is less prone to poor postdepositional preservation, yielding less biased results (Maley & Brenac, 1998; Ludemann, 2003; Di Pasquale *et al.*, 2008; Lebamba *et al.*, 2009; Colombaroli & Gavin, 2010). Furthermore, charcoal can be found in any soil type on the actual location of fire occurrence. As such, it is possible to date single fire events on any given spot where the soil charcoal archive is preserved in the ground. Pollen analysis is limited by the need for stratified lakes or bogs. Finally, macrocharcoal fragments can be identified to taxa. Wood anatomical features remain clearly visible after heating and charring of wood and after long-term burial of charcoal fragments in soil layers. Diagnostic wood anatomical features are exceptionally well defined and available for a large fraction of Central African species in the Inside Wood Database, allowing identification of individual wood and charcoal samples,

often to genus or even species level when also biogeographical distribution data are considered (IAWA IAWA Committee, 1989; Wheeler, 2011; The Inside Wood Working Group, 2012; Hubau *et al.*, 2012).

We use charcoal assemblages in stratified soil profiles to reconstruct palaeofire occurrence and vegetation change in the Kisala Singa area (profiles KS8 and KS9, see Fig. 1). This area is situated in the southernmost Mayumbe forest which is part of the network of Lower Guinean afro-montane rainforest refuges thought to be safeguarded from severe droughts (Maley, 1996, 2004). However, within the southern Mayumbe forest, the forest edges are expected to be more sensitive to climate change than the heart of the forest (Schwartz *et al.*, 1990; Maley & Brenac, 1998; Elenga *et al.*, 2004; Maley, 2004; Ngomanda *et al.*, 2007, 2009; Broadbent *et al.*, 2008). Therefore, we compare results from the heart of the southern Mayumbe forest (Kisala Singa) with those from the edge (Luki area, profiles CZ1, CZ2, CZ3, UH48) (Fig. 1) (Hubau *et al.*, 2013a).

Moreover, we compare dated palaeofire and vegetation reconstructions with the Holocene record of Lower Guinean precipitation regimes, as inferred from the meridional gradient in sea surface temperature (Δ SST) between the Southern Atlantic Ocean and the equatorial Atlantic Ocean near the mouth of the Congo River

(Fig. 1) (Kim *et al.*, 2002; Schefuß *et al.*, 2005). Specifically, high Δ SST is believed to strengthen Southern Hemisphere trade winds, which counteracts the inflow of moist air from the North Atlantic Ocean and causes more pronounced dry-season aridity (Schefuß *et al.*, 2005).

Materials and methods

Study area

The Mayumbe chain ranges from south-west Gabon over the Republic of Congo (RoC) and Cabinda down to the Congo River, along the Atlantic coastline (Fig. 1). The study area is situated in the Lower Congo province of the Democratic Republic of Congo (DRC), covering the southernmost parts of the Mayumbe hills which are between 500 m and 600 m high. The southern Mayumbe is characterized by a humid tropical climate with a long dry season of 5 months between mid-May and mid-October and a short dry season from mid-December to mid-February. Climate records are available from the Luki meteorological station (1959–2006). Yearly precipitation ranges from 649 mm to 1853 mm with a mean precipitation of 1173 mm. Temperature ranges between 19 °C and 30 °C with a mean temperature of 25.5 °C (Couralet *et al.*, 2010). Monthly average temperatures are stable during the wet season and drop slightly during the dry season. The strong oceanic influence, in combination with the hilly aspect of the region, creates favourable conditions for dense semideciduous rainforest on this relatively low latitude (Donis, 1948; Couralet *et al.*, 2010). During the dry seasons, the cold Benguela Sea Current moves to the north, affecting the Congolese shores. Cold air from the Atlantic Ocean forces warm air from the continent to rise. The rising warm air eventually becomes saturated, resulting in the formation of low-level but nonprecipitating stratiform clouds, blocking solar irradiance and decreasing temperatures and evapotranspiration. As such, the relatively low rainfall is partially compensated and a high relative air humidity is maintained (>80%).

Vegetation in the southern Mayumbe is generally classified as a tropical semi-evergreen rainforest of the Guineo-Congolian forest domain occurring in a mosaic landscape with patches of savanna and successional forest types. The rainforest consists of a mixture of deciduous and evergreen tree species in the upper stratum and mostly evergreen species in the understory (Donis, 1948; Lebrun & Gilbert, 1954; Couralet *et al.*, 2010). The most important indicator species for this forest type belong to the family of Caesalpinioideae (e.g. *Scorodophleus zenkeri*). Other indicator species belong to the families of Ulmaceae (e.g. *Celtis* spp.), Sterculiaceae (e.g. *Cola* spp.) and Meliaceae (e.g. *Entandrophragma* spp. and *Gurarea* spp.) (Lebrun & Gilbert, 1954; Maley & Brenac, 1998). *Staudtia stipitata* and *Coelocaryon* spp. are some of the most remarkable species in old climax forest. Furthermore, edaphic rainforest types occur such as monodominant *Prioria balsamiferum* stands on sandy soils (Donis, 1948). Also, the semi-evergreen mature rainforest encloses other vegetation

types which can be relatively widespread. Specific examples are Marantaceae open forests, woodland savanna types dominated by *Xylopia aethiopica* and regenerating forest dominated by *Terminalia superba*, which is especially abundant in and around the Luki reserve (Donis, 1948; Schwartz *et al.*, 1990). Most of the woodland savanna and younger forest patches are assumed to be of anthropogenic origin, although some might be relicts of palaeoclimatically induced vegetation shifts (Schwartz *et al.*, 1990; Maley & Brenac, 1998). The wooded grasslands lying in the rainshadow of the Mayumbe hills are characterized by species such as *Psorospermum febrifugum*, *Bridelia ferruginea*, *Strychnos* spp. and *Annona* spp. (Vincens *et al.*, 1998).

Charcoal sampling and profile description

Charcoal fragments (largest dimension >2 mm) were carefully collected by hand per interval of 10 cm in two pedoanthracological profiles with a surface area of 1.5 m² and a total depth of 140 cm. The profiles are situated in the Kisala Singa area (profiles KS8 and KS9, see Fig. 1), which is a remote and intact part of the southern Mayumbe forest characterized by densely forested steep slopes. Specific anthracomass was calculated per profile interval following standard procedures (Carcaillet & Thion, 1996).

After excavating the profile, abundances of roots and stones were estimated (Volume%) and soil wet colour was identified using the Munsell soil colour chart. Finally, one representative profile wall was selected to carefully collect undisturbed soil samples per profile interval using knife and spatula. Thin sections were prepared from these undisturbed soil samples, following polyester impregnation using standard procedures. Micromorphological features were described applying polarization microscopy, using standard concepts and terminology (Murphy, 1986; Stoops, 2003; Stoops *et al.*, 2010). These features reveal variations in texture and possible bioturbation. Procedures for charcoal sampling and profile description were largely the same for the Luki profiles (for full details, see Hubau *et al.*, 2013a).

Profile stratigraphy and radiocarbon dating

For each profile interval, up to 50 charcoal fragments were studied using reflected light microscopy and grouped into charcoal types. Each type represents a group of species matching the charcoal anatomy (Hubau *et al.*, 2012). Profile stratigraphy was deduced from micromorphological soil features, the distribution of anthracomass and the distribution of charcoal types. Profile stratigraphy was verified using constrained cluster analysis of charcoal type abundance data. Cluster analysis was performed with the Rioja package in R (Juggins, 2012). Sequential zonation was obtained by optimal sum-of-squares zonation, using the broken-stick model to estimate the number of statistically different profile depth zones (Birks & Gordon, 1985; Bennett, 1996). In each stratigraphic interval, up to three charcoal fragments were selected for AMS radiocarbon dating. Calibration was performed with the OXCAL v4.1.5 software (r:5) using the

SHCal04 southern hemisphere 14C calibration curve (McCormac *et al.*, 2004; Bronk Ramsey, 2009).

Charcoal type description and identification

An example fragment per charcoal type was chosen for detailed visualization using scanning electron microscopy and laboratory-based high-resolution X-ray CT (Van den Bulcke *et al.*, 2009; Hubau *et al.*, 2013a,b) for detailed anatomical description using well-defined features (IAWA Committee, 1989; Wheeler, 2011). Each charcoal type was identified using a recently developed protocol (for a detailed discussion, see Hubau *et al.*, 2012) using a database of more than 2900 woody species. This database enables a directed search taking into account metadata on (1) anatomical features, (2) availability of thin sections within the reference collection, (3) species distribution and (4) synonymy. The protocol starts with an anatomical query within the database, proceeds with automatic extension and reduction phases of the resulting species list and ends with an in-depth comparative microscopic study of wood reference thin sections and charcoal anatomy. During this last phase of the protocol, species are evaluated based on a wide range of anatomical features. The final result of the charcoal identification protocol is a small group of retained species, which are all given a probability ranking. To do so, a 5-point grading system is used, subject to the identifier's opinion: the degree of resemblance ranges from 'almost perfectly' (5 points attributed) to 'only moderately' (only 1 point attributed). After identification, each charcoal type receives a 9-character label consisting of the three first letters of family, genus and species name of one of the best ranked species (Hubau *et al.*, 2012).

Finally, each charcoal type is assigned to a vegetation type for palaeoecological interpretation. This is based on the vegetation type of the best ranked species retained after identification. Information on ecology, distribution and occurrence in vegetation types is derived from Lebrun & Gilbert (1954), Burkill (1985) and Protabase (2012).

Evaluation of identifications

All identifications were evaluated according to two criteria. Evaluation criterion A reflects whether the highest ranked species have similar phytosociological characteristics, that is phytosociological propinquity. If the highest ranked species occur in the same vegetation type, the charcoal type receives a positive score for evaluation criterion A (= phytosociological propinquity). In cases where there are several highest ranked species which occur in different ecological settings (i.e. different phytosociological characteristics), palaeoecological interpretation of the charcoal type is complicated. In such cases, the charcoal type receives a negative score for evaluation criterion A (= phytosociological ambiguity).

Evaluation criterion B is based on the number of highest ranked species and their anatomy rank, with a higher score with increasing degree of resemblance between charcoal and wood anatomy. Based on both criteria, the charcoal type was assigned to one of six identification reliability ranks, which

allows a distinction between strong and weak identifications (Hubau *et al.*, 2013b).

Results

Palaeofire occurrence

Each charcoal type in the KS8 profile is confined to one of five zones (0–30 cm, 30–60 cm, 60–80 cm, 80–120 cm and 120–140 cm depth) corresponding with five distinct anthracomass peaks that are separated by charcoal-poor intervals (Figs 2, 3 and S1). This suggests that profile KS8 contains five different charcoal assemblages originating from five different single wildfire events (= palaeofires). This is confirmed by constrained cluster analysis, which yields exactly the same five zones as deduced from anthracomass and charcoal type distribution patterns (Fig. 3). Radiocarbon dating results show that the palaeofires occurred during five different epochs: around 0.4, 0.7, 1.8, 2.3 and 6.8 ka BP, respectively. Likewise, the KS9 profile is stratified with three distinct anthracomass peaks (10–20 cm, 30–40 cm and 70–80 cm intervals) (Fig. 4) representing charcoal assemblages originating from three different fire events that occurred around 0.25, 1.65 and 7.8 ka BP (Figs 5 and S2).

Figure 6 compares palaeofire occurrences in the Kisala Singa area (KS8 and KS9; Fig. 6a) in the heart of the Mayumbe forest with those of the Luki reserve at the edge of the forest (CZ1, CZ2, CZ3 and UH48; Fig. 6b). Together, the six profiles yielded 13 distinct charcoal assemblages that were formed during 13 different wildfire events (= palaeofires). These wildfire events occurred during three distinctly separated periods of palaeofire occurrence (arrows on top of Fig. 6): 7.8–6.8 ka BP, 2.3–1.5 ka BP, 0.8 ka BP–present.

Vegetation reconstruction

In total, 868 charcoal fragments from the KS8 and KS9 profiles were analysed and grouped into 52 charcoal types, from which 38 were identifiable (Figs 3 and 5). From the profiles in the Luki reserve (UH48, CZ1, CZ2, CZ3), a total of 935 charcoal fragments were analysed, yielding 44 identified charcoal types (Hubau *et al.*, 2013a). Grey scales in Figs 3 and 5 represent the phytosociological classification of the charcoal types found in each charcoal assemblage. Identification details of all identified charcoal types of the Kisala Singa and Luki profiles are presented in Table S1, specifying the number of retained species after identification and a phytosociological classification of each charcoal type. This table also presents an identification reliability evaluation for each charcoal type. Identification reliability in

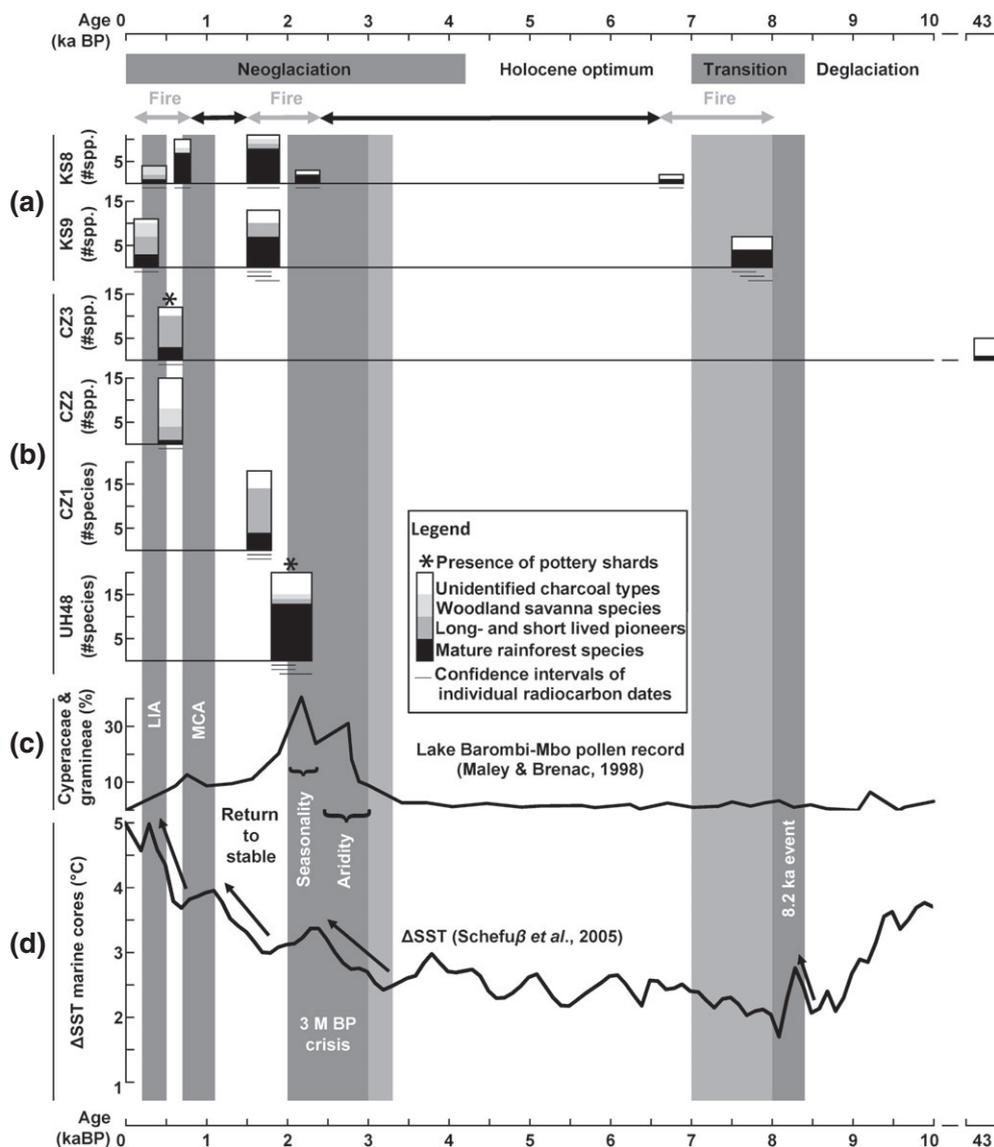


Fig. 6 Charcoal-inferred palaeofire and vegetation reconstructions in context. Comparison of palaeofire occurrence and vegetation composition of the heart (a) and the edge (b) of the Mayumbe forest, with selected other vegetation (c) and climate (d) records. Main disturbance periods are indicated with grey bands: the 8.2 ka BP event, the third millennium BP crisis, the Mediaeval Climate Anomaly (MCA) and the Little Ice Age (LIA) (Maley, 1996, 2004; Maley & Brenac, 1998; Elenga *et al.*, 2004; Ngomanda *et al.*, 2007, 2009). (a) Overview of the compositions of charcoal assemblages formed during wildfires in the Kisala Singa area (profiles KS8, KS9). Bar height represents the number of species in the charcoal assemblage, grey scales represent vegetation types: black = mature rainforest; intermediate grey = regenerating forest; light grey = woodland savanna; white = unidentified types. All dates are given in calendar years before present, with present set at 1950 AD. The lines just under the bars represent the 2σ confidence intervals after calibration for each of the individual radiocarbon dates performed in that charcoal assemblage. The bar width spans all confidence intervals of the radiocarbon dates in that charcoal assemblage. (b) Overview of the compositions of charcoal assemblages formed during wildfires in the Luki reserve (profiles UH48, CZ1, CZ2 and CZ3) (Hubau *et al.*, 2013a). Bar width represents the 2σ confidence interval after calibration. An asterisk (*) indicates the presence of pottery shards in the profile interval. (c) Abundance of savanna and hygrophilous species (Cypereaceae and Gramineae) in the Barombi-Mbo pollen record (Maley & Brenac, 1998). (d) Δ SST = difference in Sea Surface Temperatures between the tropics (marine core GeoB 6518-1) and the subtropics (marine core GeoB 6518-1) (Schefuß *et al.*, 2005). Arrows indicate rising Δ SST. Marine cores are localized in Fig. 1.

Discussion

Climate–fire–vegetation linkage

The two oldest recorded palaeofires in the heart of the Mayumbe forest occurred around 7.8 ka BP (KS9) and 6.8 ka BP (KS8) (Fig. 6a). They illustrate the significance of the abrupt Early to Mid-Holocene climatic transition (~ 8.2 ka BP event), associated with the final retreat of continental ice sheets and distinct aridification in Central Africa (Stager & Mayewski, 1997; Alley & Ágústsdóttir, 2005). This climate anomaly has barely been covered by other Lower Guinean palaeorecords. Although the occurrence of fires indicates forest disturbance, charcoal identification results indicate that mature rainforest persisted in the heart of the Mayumbe forest (Kisala Singa area, KS8 and KS9 sites) after the 8.2 ka BP event (Figs 3 and 5). The occurrence of fire events in mature rainforest can probably be attributed to lower relative air humidity in the canopy, facilitating ignition (Cochrane, 2003).

Furthermore, the stratigraphies of profiles KS8 and KS9 reveal a remarkable absence of fire between 6.8 and 2.3 ka BP. This period roughly coincides with the Holocene thermal optimum and the end of the African Humid Period, which was a phase of distinct forest expansion in Central Africa and the warmest period on a global scale during the Holocene (Maley, 1996; Marret *et al.*, 2006). Gently rising Δ SST (Schefuß *et al.*, 2005; see Fig. 6d) did not provoke forest fire occurrence (Fig. 6a, b). The absence of palaeofires during this period can probably be attributed to generally low Δ SST and high levels of relative air humidity, reducing flammability (Scott, 2000; Cochrane, 2003). The Mayumbe forest might have transgressed current fragmented forest limits during that period (Fig. 1b) (Maley, 1996, 2004).

After the Holocene thermal optimum, Δ SST started to rise steeply, a trend that continued over the last three millennia (Schefuß *et al.*, 2005; see Fig. 6d). This caused progressive aridification and a permanent fire-prone state of open vegetation patches, explaining the abundance of recorded fire events during that period as opposed to the Holocene thermal optimum (Fig. 6a, b). Initial aridification between 3.5 and 2.5 ka BP resulted in a first phase of lowland rainforest breakdown as indicated by pollen records from the Lower Guinea (light grey band in Fig. 6a) (Maley, 1996, 2004; Reynaud-Farrera *et al.*, 1996; Maley & Brenac, 1998; Elenga *et al.*, 2004; Ngomanda *et al.*, 2009). Pollen evidence indicates that this breakdown phase was particularly significant at the margins of the rainforest (Ngomanda *et al.*, 2009). Although few palaeofires were recorded in the Ituri forest to the East of the Congo Basin (Hart

et al., 1996), our palaeofire reconstruction shows that fires during this period were probably scarce, even at the southernmost edge of the Central African rainforest complex (Fig. 1). This could indicate that increasing aridity between 3.5 and 2.5 ka BP did not have major breakdown effects due to fire. Closed canopy rainforests are indeed considerably resistant to drought and fire because they can trap transpired moisture within the canopy, which reduces flammability (Scott, 2000; Cochrane, 2003).

The second half of the third millennium BP, however, was characterized by an increase in seasonality (dark grey band in Fig. 6) (Maley & Brenac, 1998; Elenga *et al.*, 2004; Maley, 2004; Ngomanda *et al.*, 2009; Neumann *et al.*, 2012a). Rising Δ SST strengthened trade winds and a subsequent southward shift of the ITCZ caused very pronounced and long dry seasons (Elenga *et al.*, 2004; Schefuß *et al.*, 2005; Ngomanda *et al.*, 2009; Neumann *et al.*, 2012a). Storm tracks during wet seasons created forest gaps that were vulnerable to drought and fire during intense dry seasons. This resulted in the development of fire-prone forest–savanna mosaics (Fig. 6c) (Schwartz *et al.*, 1990; Maley & Brenac, 1998; Broadbent *et al.*, 2008; Ngomanda *et al.*, 2009). Five recorded charcoal assemblages indicate that fire affected both the heart (KS8 and KS9, Fig. 6a) and the edge (Luki, CZ1-3, UH48, Fig. 6b) of the southern Mayumbe forest at the end of the third millennium BP and continued disturbing the forest until 1.5 ka BP. Nevertheless, identification results indicate that this crisis probably did not change forest composition in the heart of the Mayumbe rainforest during and after the third millennium BP (Kisala Singa area, Fig. 1b): charcoal assemblages are mostly dominated by typical mature semideciduous rainforest taxa. Yet, mature rainforest locally disappeared at the edge of the southern Mayumbe forest during the rainforest crisis and regenerated afterwards as suggested by the dominance of pioneer taxa in the CZ1 assemblage.

The last period of remarkable palaeofire abundance coincides with two shortly following well-known climate anomalies: the Mediaeval Climate Anomaly (MCA, 1.1–0.7 ka BP) and the Little Ice Age (LIA, 0.65–0.15 cal kyr BP) (Fig. 6). Pollen records indicate an increase in shade-intolerant taxa during the MCA in the Lower Guinea, caused by fluctuating wet–dry conditions (Ngomanda *et al.*, 2007; Brncic *et al.*, 2009). Furthermore, climate would have been generally dry throughout western and central tropical Africa during the second part of the LIA (0.5–0.15 cal kyr BP) (Verschuren *et al.*, 2000; Russell & Johnson, 2007; Verschuren & Charman, 2008). This is in line with a remarkable dominance of charcoal types belonging to pioneer, liana and woodland savanna taxa in both

the heart (KS8, KS9) of the southern Mayumbe forest and the forest edge (CZ2, CZ3) after 0.8 ka BP (Fig. 6a, b).

As a conclusion, the three periods of palaeofire occurrence indicated by arrows in Fig. 6 can be associated with three well-known climate anomalies recorded in other Lower Guinean palaeorecords (Fig. 1a): the 8.2 ka BP event, the third millennium BP rainforest crisis and the Mediaeval Climate Anomaly, respectively (dark grey bands in Fig. 6). These Holocene climate anomalies are associated with distinct Δ SST peaks, indicating increased aridity (Fig. 6d) (Schefuß *et al.*, 2005). These pronounced arid events probably resulted in a fragmented forest structure with fire-prone open patches, as illustrated by peaking concentrations of savanna pollen in the Lake Barombi-Mbo record, Cameroon (Fig. 6c) (Maley & Brenac, 1998). Our palaeofire reconstruction in Fig. 6 indicates that some fires occurred during the climate anomalies, although most fires seem to lag behind them, sometimes for centuries. This suggests that open patches remained fire-prone after the actual climate anomalies. As such, forest regeneration was seriously hampered by fire and could take up to 500 years (Cochrane, 2003). The scarcity of recorded palaeofire events during the actual climate anomalies could be explained by a temporary disappearance of woody vegetation and a related increase of erosion, eventually resulting in discontinuities in the charcoal record.

Vegetation dynamics

Identification results indicate that mature rainforest persisted on the KS8 and KS9 sites until 0.8 ka BP, through the Early to Mid-Holocene climatic transition, the subsequent Holocene thermal optimum and the third millennium BP rainforest crisis (Fig. 6). The Kisala Singa forest could have been dominated by mature semideciduous rainforest until the last millennium BP, despite perturbation and fire occurrence. The area belongs to a postulated rainforest refuge that is thought to be safeguarded from climate anomalies due to its geographic location (Maley, 1996; Sosef, 1996). Especially, the KS8 profile reveals an episodic pattern of fire occurrence. Two fires shortly followed each other between 2.3 and 1.8 ka BP. Identification results indicate that the two shortly successive fires each burned a mature rainforest stand. This suggests that forest regeneration after the 2.3 ka BP event was relatively fast, obtaining a species composition typical for mature forest within centuries.

Analogous to the Kisala Singa area, mature rainforest patches also survived through the third millennium BP crisis in the Luki reserve, as illustrated by the UH48

assemblage. Yet, the dominance of pioneers in the CZ1 assemblage indicates that mature rainforest locally disappeared during or after the rainforest crisis and was regenerating around 1.8 ka BP, which is in line with increased pioneer abundance in most Lower Guinean pollen records during the first part of the second millennium BP, when favourable conditions temporarily returned (Reynaud-Farrera *et al.*, 1996; Elenga *et al.*, 1996; Elenga *et al.*, 2004; Maley & Brenac, 1998; Ngomanda *et al.*, 2007, 2009). This indicates that disturbance and fragmentation were perhaps more prominent near the boundary of the southern Mayumbe forest (Luki) than in the Kisala Singa area in the heart of the southern Mayumbe forest.

Rainforest resilience to perturbation, however, seems to be absent during the last fire period (0.8–0.25 ka BP) even in the heart of the southern Mayumbe forest. On the KS8 site, a mature rainforest stand was burned in a first fire event (0.8 ka BP), while a second shortly following event (0.4 ka BP) burned a mixture of mature rainforest species, prominent pioneers and woodland savanna species. Furthermore, the dominance of woodland savanna species, long-lived pioneers and short-lived pioneers in the 0.25 ka BP KS9 (Fig. 6a), the CZ2 and the CZ3 assemblages confirm that forests were probably fragmented in both the Kisala Singa and the Luki areas after 0.8 ka BP (Fig. 6, see also Hubau *et al.*, 2013a). This is in line with the pattern of rising Δ SST, indicating progressively drier conditions hampering forest regeneration (Schefuß *et al.*, 2005; see Fig. 6d). This also indicates that the two shortly following climate events (the MCA and the LIA) in the last century did have a significant influence on rainforest composition in the southern Mayumbe.

As a conclusion, the KS8 results together with the identification results of the other profiles reveal two general trends. First, rainforest could rather easily recover from fire and drought until 0.8 ka BP. Secondly, rainforest regeneration was hampered by increasingly severe drought conditions after 0.8 ka BP.

Role of human activity

Although correspondence between Δ SST variation and periods of palaeofire occurrence and forest fragmentation provide evidence for a natural climatic control of Holocene Central African palaeofire and vegetation change, a persistent 'burning' question is which effect human activity has had, especially during the last centuries. Three of thirteen fire events presented in Fig. 6 took place before the onset of Bantu migrations: the 6.8 ka BP KS8 event, the 7.8 ka BP KS9 event and the >43.5 ka BP CZ3 event. These palaeofires were likely naturally ignited by lightning strikes during thunder-

storms in the dry season (Hart *et al.*, 1996; Scott, 2000; Williams & Satori, 2004). All other recorded fire events, however, are younger than 2.5 ka BP, which means they occurred in an area where settlers were present who could have used slash-and-burn techniques.

In general, archaeological evidence for anthropogenic influence on the vegetation in the Lower Guinea is scarce (Neumann *et al.*, 2012a). Archaeological sites indicate the presence of Bantu-speaking people in the western part of the Republic of Congo since the third millennium BP (Denbow, 1990, 2012; Schwartz *et al.*, 1990). Bantu-speaking migrants introduced farming and iron smelting in the Lower Guinea, impacting the surrounding forest (Schwartz *et al.*, 1990; Bayon *et al.*, 2012; Neumann *et al.*, 2012a). However, farming was most likely only a minor activity until the last millennium (Brncic *et al.*, 2007, 2009; Neumann *et al.*, 2012a; Tovar *et al.*, 2014). Furthermore, early migrants in the Lower Guinea settled preferably in easily accessible areas. Examples are the Atlantic coastal savannas in the Republic of Congo such as the Tchissanga, Loubanzi and Madingo-Kayes sites (Denbow, 2012) and the savanna area of the Lower Congo South of the Congo River such as the Sakusi and Ngovo sites (de Maret, 1990). The only archaeological sites located in the southern Mayumbe forest are Lukula (Hubau *et al.*, 2014), La mare du Flec (de Foresta, 1990; Schwartz *et al.*, 1990) and the Sumbi site (Clist, 2012). For maps and a more thorough discussion, see Clist, (2012) or Hubau *et al.* (2014).

The higher number of archaeological sites in accessible regions is to some extent possibly a bias, because these regions are also better accessible to archaeologists. However, the roughness of the topography has safeguarded the Kisala Singa forest from exploitation during the last century, despite heavy logging activities all over the Lower Congo (Donis, 1948). Likewise, the steep and densely forested slopes might have discouraged early migrants. Also, settlers prefer cutting soft pioneer trees instead of the denser and harder mature rainforest trees (Neumann *et al.*, 2012a,b; Hubau *et al.*, 2014). Therefore, they were probably more attracted by fragmented areas with a high abundance of regenerating forest such as forest edges. This could perhaps explain the absence of any artefact in the KS8 and KS9 profiles, which are located in the heart of the southern Mayumbe forest. Charcoal from these profiles is likely of natural origin, indicating natural fire occurrence linked to drought events. In contrast, the Luki profiles are excavated at the edge of the southern Mayumbe forest, where slopes are less steep and where the forest was probably more prone to fragmentation (Cochrane, 2003). This could explain the presence of charcoal assemblages that probably originate from human activ-

ity in profiles UH48 (2.1 ka BP) and CZ3 (0.6 ka BP). The role of human activity is indicated by the presence of a few small pottery shards and oil palm endocarps (Hubau *et al.*, 2012, 2013a). These two fire events were probably not a direct result of drought anomalies although population densities and migration patterns of humans in the Central African rainforest is strongly related to climate variability (Neumann *et al.*, 2012a,b). Climatic anomalies were likely a driving force triggering episodes of increased palaeofire occurrence, forest fragmentation and slow regeneration lasting multiple centuries. Meanwhile, they also forced human migrations in the Lower Guinea, whom reinforced the effects of climate deterioration, especially during the last millennium BP (Salzmann & Hoelzmann, 2005; Brncic *et al.*, 2007, 2009).

Uncertainties and opportunities

A key-hole picture. Our results show that terrestrial charcoal archives are useful for tracing fires, relating fire history to climate anomalies and reconstructing the composition of burnt vegetation types in Central Africa. The information from terrestrial charcoal archives is local, which offers the possibility of accurately tracing the zonal vegetation of a certain (small) area, in contrast to pollen analysis which sometimes gives biased results due to long-distance pollen transport, species-specific transport and poor postdepositional preservation (Malley & Brenac, 1998; Ludemann, 2003; Di Pasquale *et al.*, 2008; Lebamba *et al.*, 2009; Colombaroli & Gavin, 2010). However, the analysis of local data only gives a key-hole picture of the specific study sites. Therefore, more sites need to be investigated in order to underpin general conclusions concerning larger regions.

Differences in fire frequency. The successive charcoal peaks in the KS8 profile become progressively larger over time (from 0.6, 9, 43, 466, 1054 ppm; see Fig. 2) which might indicate a positive feedback cycle between fire frequency and fire intensity (Cochrane *et al.*, 1999; Cochrane, 2003). This contrasts with the low specific anthracomass peaks recorded in the Luki reserve (15 ppm in CZ1 and 11 ppm in CZ2; see Hubau *et al.*, 2013a). If charcoal abundance is linked to fire intensity (e.g. Carcaillet & Thion, 1996; Tovar *et al.*, 2014), this might indicate lower fire intensity during the events recorded in the Luki reserve. Furthermore, as there is positive feedback between fire intensity and fire frequency, this might perhaps also indicate a lower fire frequency in the Luki reserve. Indeed, the two Kisala Singa profiles each gave evidence for several palaeofires, which contrasts with the CZ1 and CZ2 profiles from Luki, with only one palaeofire each. The Luki reserve, however, is

expected to be more sensitive to climate change and palaeofire occurrence due to its position at the boundary of the southern Mayumbe forest (Cochrane *et al.*, 1999; Cochrane, 2003).

This apparent discrepancy can be explained by gaps in the charcoal record. If palaeoclimate anomalies indeed affected the forest edges severely (Maley & Brenac, 1998; Ngomanda *et al.*, 2007, 2009), the vegetation in and around the Luki reserve could have been locally and temporarily replaced by very open savanna types. As savanna environments are prone to erosion and chemical weathering, soil accumulation and charcoal burial during these periods could have been restricted, eventually resulting in the loss of charcoal assemblages (Bayon *et al.*, 2012). Also, charcoal fragments resulting from fires in savanna environments are mainly from grasses and herbs. These fragile charcoal fragments can be found in lake sediments (Colombaroli *et al.*, 2014; Tovar *et al.*, 2014), on pollen slides (Scott, 2000; Forbes *et al.*, 2006) or by a refined soil washing protocol (Carcaillet & Thion, 1996), but they are very difficult to detect by hand-picking. Also, they are easily wind-blown and scattered over large distances. As such, the pedoanthracological record in Fig. 6 might not cover all palaeofires, particularly not those that occurred during the actual dry climate anomalies when rainforest cover was heavily reduced.

Additionally, the scarcity of (older) palaeofire events in the nonstratified Luki profiles (CZ1, CZ2, UH48) could be explained by differences in profile development processes. A first important difference between the nonstratified (CZ1, CZ2, UH48) and the stratified (CZ3, KS9 and KS8) profiles is that the latter were excavated in relatively shallow soils, limited by a dense stone and gravel layer between 50 and 100 cm (Figs 2 and 4). Bocek (1986) describes vertical separation of objects according to size, indicating that large stones might be buried at a slower rate than (smaller) charcoal fragments (see also Balek, 2002). As such, the presence of a dense layer of stones larger than the charcoal fragments may have slowed down charcoal burial in these profiles. In contrast, charcoal fragments were perhaps able to migrate more freely through profiles without stones (CZ1, CZ2, UH48), resulting in the spreading of a single charcoal assemblage over a depth of 140 cm (for figures, see Hubau *et al.*, 2013a). As Holocene soils can be several metres thick in Central Africa, older charcoal layers could perhaps be present deeper down the nonstratified soil profiles (Thiéblemont, 2013). A second difference between the nonstratified (CZ1, CZ2, UH48) and the stratified (CZ3, KS9 and KS8) profiles is the set of micromorphological features of soil thin sections indicating colluvial sediment deposition. The nonstratified profiles include chert fragments (CZ1,

CZ2), ironstone fragments (CZ2, UH48), relatively low grain angularity (UH48) and good sorting (UH48) (for terminology and interpretation, see Stoops, 2003 and Stoops *et al.*, 2010). In contrast, high grain angularity, poor sorting and the absence of chert or ironstone fragments indicate a lower rate of colluvial deposition for the KS8 and KS9 profiles (Figs 2 and 4), which might also explain lower charcoal burial rates.

Postdepositional profile disturbance. Postdepositional soil development processes often disturb profile stratification although they are complex and can be very different from site to site (Balek, 2002). All profiles presented in Fig. 6 are characterized by bioturbation, as evidenced by the study of micromorphological features on thin sections of undisturbed soil samples, showing the occurrence of channels, passage features and zones with a pellet or granular microstructure (see Hubau *et al.*, 2013a for details). Ants, termites, worms, burrowing animals and roots are abundant in the rainforests of the southern Mayumbe, translocating small and relatively large objects in soil profiles (e.g. Cahen and Moeyersons, 1977; Bocek, 1986; McBrearty, 1990; Balek, 2002; Théry-Parisot *et al.*, 2010). However, the KS8 and KS9 profiles are clearly stratified as shown by the presence of separate anthracomass peaks and the distribution of charcoal types, showing that charcoal types are mostly confined to only one of the peaks (Figs 3 and 5). Furthermore, profile stratigraphy was verified using constrained cluster analysis of charcoal type abundance data (Birks & Gordon, 1985; Bennett, 1996; Juggins, 2012). The constrained cluster analysis dendrogram for the KS8 profile shows five significantly different depth zones at the 5th level of similarity (Fig. 3). Similarly, the KS9 dendrogram shows three significantly different depth zones (Fig. 5). These depth zones coincide exactly with the anthracomass peaks (five and three peaks for the KS8 and KS9 profiles, respectively). Finally, radiocarbon dating of a charcoal fragment from each depth zone shows significantly different ages for each depth zone. Moreover, the ages are progressively older when going deeper into the profile, as also illustrated by the age–depth models in Figs S1 and S2.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Depth–Age relationship for the KS8 profile. Horizontal bars represent the 2σ confidence intervals after calibration.

Figure S2. Depth–Age relationship for the KS9 profile.

Table S1. Identification results per charcoal type.