



Invited Review Article

Ancient charcoal archives for understanding palaeofire regimes, sedimentary processes and vegetation changes in the rainforests of Central Africa: review and challenges

Pierre Giresse^a, Bernard Clist^{b,e}, Alex Chepstow-Lusty^{c,*}, Jean Maley^d

^a CEFREM, UMR 5110 CNRS, Université de Perpignan Via Domitia, France

^b Institut des Mondes Africains (IMAF), Paris, France

^c Department of Geography, University of Sussex, Brighton BN2 4GJ, United Kingdom

^d Institut Sciences de l'Evolution-Montpellier (ISEM-CNRS), Université de Montpellier. IRD, Montpellier, France

^e Collège de France, Paris, France

ARTICLE INFO

Editor: Fabienne Marret-Davies

Keywords:

Palaeofires
Palaeoclimate
Charcoal
Central Africa
Rainforest
Holocene

ABSTRACT

On the African continent, the relationship between palaeofire regimes and vegetation changes is quite well-documented in savannas or the transitional areas from savannas to forests where human-caused burning can regulate the rhythms of natural fires and reduce their size and frequency. In contrast, this relationship remains poorly known in the vast rainforest where a growing number of palaeostudies highlight the difficulties in associating societal responses with environmental changes. Considering the vast forest biome of Central Africa, the main challenge is distinguishing between climatic drivers, vegetation changes, and possible human impacts. The recurring weakness is the uncertainty of estimating past human population densities in Africa – a parameter relatively well-documented on other continents and often essential in understanding fire regimes. As such, fires and charcoal are often primarily used to frame the question of environmental changes caused by anthropogenic impacts in the past. However, this approach appears to ignore the available evidence that in early Holocene times, human densities in Central Africa were very low, with many records suggesting the major preponderance of climatic factors, and human action being considered as an uncertain hypothesis.

The archaeological remains found represent a wide variety of activities, and indicate that perceived fuelwood quality depended on activity-specific requirements. Hence, the selection or non-selection of fuelwood is related to the abundance or scarcity of locally available plant biomass. Nevertheless, “cultural biases” – in terms of species selection – can mean that charcoal assemblages do not provide valid reconstructions of past vegetation. In addition, other issues with such archaeological deposits include the potential absence of age-depth relationships due to soil profile mixing (pedoturbation) resulting from biotic or abiotic agents, with the upper soil layer even containing a mixture of both recent and ancient charcoal. However, a few privileged sites have allowed the development of robust chronostratigraphies and palaeogeographic reconstructions based on *in situ* charcoal.

1. Introduction

Central African rainforests do not comprise a single block of forests, but instead encompass various evergreen forest and semi-deciduous forest types (Fig. 1), with tree species sensitive to low temperatures or low light intensities in the dry season, and to seasonal changes in evapotranspiration rates (Pfeifer and Shirima, 2021). Rainfall is only locally sufficient to maintain biomass (Sheil et al., 2019), while certain forests may respond to limited water availability with canopies opening

up, and becoming more prone to fires and less carbon dense (e.g. Sullivan et al., 2017). There is a modern consensus to propose a threshold for fire suppression occurring at ca. 40% woody cover (Archibald et al., 2009; Cardoso et al., 2018; Hoffmann et al., 2012; Sankaran et al., 2005; Staver et al., 2011). Notably, higher tree canopy cover excludes fuel-producing grasses (particularly the most flammable), thus resulting in smaller, higher moisture-content fuel loads. The proximal zones to forest areas are also considered insofar as they represent ecological transitional zones, which are the most sensitive to threshold effects. Unlike the

* Corresponding author.

E-mail address: alexchepstow@gmail.com (A. Chepstow-Lusty).

<https://doi.org/10.1016/j.gloplacha.2025.105174>

Received 22 April 2025; Received in revised form 27 October 2025; Accepted 9 November 2025

Available online 10 November 2025

0921-8181/© 2025 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

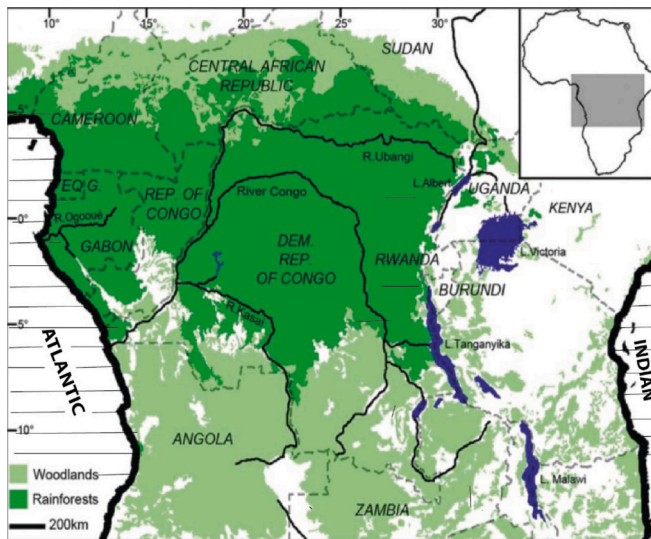


Fig. 1. Current distribution of rainforests and semi-deciduous woodlands in Central Africa; white areas are savannas (after Taylor, 2016).

apparently stable forest areas, on the scale of the last millennia, these transitional zones are particularly likely to record the impacts of the more recent climatic oscillations.

Considering the number and size of fires, fire intensity, frequency and seasonality in African grassy ecosystems, it is clear that the impacts of rainforest fires have been less investigated (Archibald, 2016; Bremond et al., 2024). However, of the 24 palaeoenvironmental sites previously analysed from the Central African rainforest over the last few millennia (Giresse et al., 2023; Fig. 2), only seven provide charcoal records, and these are located in or on the margins of open forest.

As such, fire occurrences may have been controlled by a combination of factors, including fuel availability, heat, frequency of lightning and

persistence of moisture. Thus, in a fairly general way, under dry and warm climates, when savannas expanded, such as during the Late Holocene Rainforest Crisis, ca. 2500–2000 cal BP (henceforth noted yr BP), fire occurrences increased. Conversely, warm and humid climates, as during the African Humid Period of the Early Holocene, promoted rainforests and reduced fire ignition and spread. Current observations show that Central African rainforest fires tend to be slow-spreading and of low intensity due to high humidity and the absence of high winds (Cochrane, 2003). It is therefore probable that long-distance charcoal particle transport in tropical forests is limited in comparison with savanna ecosystems (McMichael et al., 2012; Tovar et al., 2014). It is suggested that local and small size-area fires do not disseminate a significant number of charcoal particles in forested areas except when the recording site is very close to the fires (Aleman et al., 2013). However, uncertainties remain in connecting large-scale climatic trends to local weather events, let alone weather events to human activities in the distant past (Degroot et al., 2021).

Ecosystem flammability is determined by a complex interplay of climatological and ecological factors that influence the amount of biomass available to burn and its moisture content (Pausas and Fernandez-Muñoz, 2012; Simpson et al., 2016). To simplify the causalities, charcoal can be produced either from natural fires during dry periods, in relation to thunderstorms (e.g. Tutin et al., 1996), or from anthropogenic activities linked to land clearance (Cochrane, 2003). This uncertainty applies to the whole of the African continent and, even more, to areas covered by dense evergreen forest, with the density and quality of the palaeodata remaining notably fragmentary (Bremond et al., 2024).

The palaeoenvironmental significance of charcoal accumulation in African forests is a part of the history of climate and society (Degroot et al., 2021), and the subject for ever increasing publications. Nevertheless, even if the lessons drawn from it remain controversial and continue to foster debate, a clarification and synthesis seems highly topical and drives the current review.

Do the fires reflect increasing demographic pressure, i.e. more people meaning more charcoal deposited – or rather favourable climatic

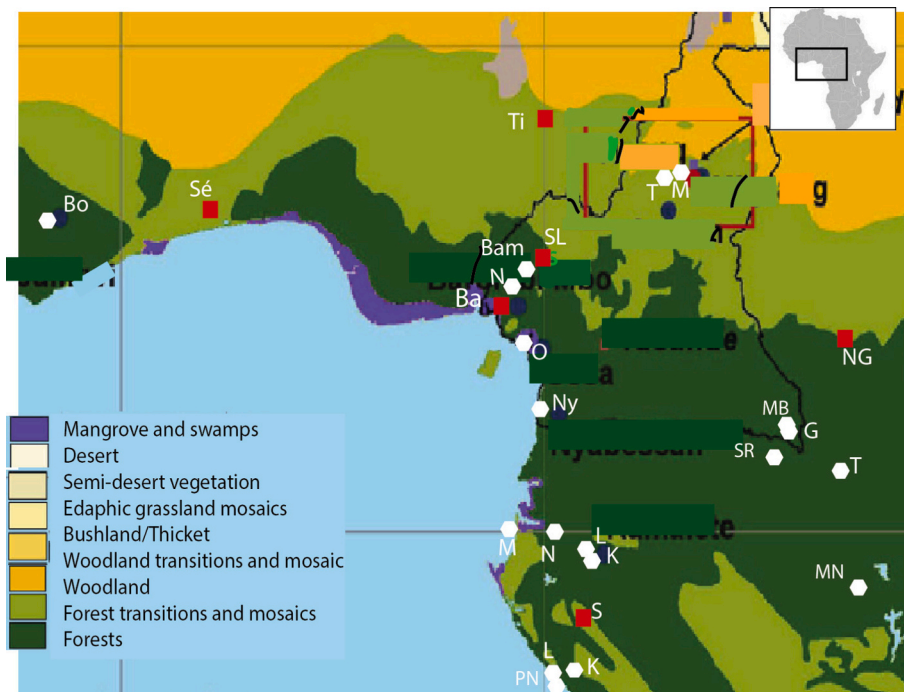


Fig. 2. Location of lakes, swamps and marshy forests providing palaeorecords (up to 5 kyr) from tropical West Africa. PN: Pointe-Noire, L: Loango-Diosso, K: Kitina, S: Sinnda, K: Kamalété, L: Lopé marsh, N: Nguène, M: Maridor, Ny: Nyabassa, O: Ossa, Ba: Barombi-Mbo, N: Njupi, Bam: Bambili, SL: Shum Laka, Mb: Mbalang, T: Tizong, MB: Mopo Bai, G: Goualougou, SR: Sangha River Interval, NG: Ngotto, T: Télé, MN: Mai Ndombe, Bo: Bosumtwi, Sé: Sélé, Ti: Tilla. The phytogeographical base map is adapted from Nguetsop et al. (2013).

conditions leading to more vegetation being transformed into charcoal?

Potential traces of anthropogenic fires, probably facilitated by lightning strikes creating bush fires, are regularly identified since ca. 1.5 million years ago in the archaeological record and associated with *Homo erectus* (Gowlett and Wrangham, 2013; Gowlett, 2016). Much later, evidence of organized hearths has been found from around 0.7 to 0.4 million years. Nevertheless, in those ancient times, probably due to the very low density of land use by hominids, it can be posited that their impact was negligible. Chronological control of wood charcoal present in palaeoreconstructions only becomes useful after ca. 60,000–50,000 cal BP, i.e. the limit of radiocarbon dating. In Central Africa, the oldest radiocarbon date comes from the Maboué 5 site in central Gabon ($\geq 57,100$ cal BP; see Mesfin et al., 2021).

To provide a broader long-term palaeoenvironmental perspective on burning in relation to the dynamics of tropical African rainforests, marine archives were examined due to their greater potential for providing continuous and well-dated, largely undisturbed sequences of exported terrestrial material. The recurrence of charcoal accumulations is attested from oceanic sediments at various latitudes on the scale of several million years, i.e. through periods when the presence and especially the density of the first hominids remains unknown.

Focusing on the sedimentary basins from the margins of the African continent, pioneering studies (Bird and Cali, 1998, 2002) have made it possible to highlight periods of intense charcoal accumulation in response to favourable palaeoclimatic conditions on the adjacent continent. A sediment core was collected from the top of the Sierra Leone Rise, a little north of Central Africa. Charcoal was transported to the marine depths by prevailing winds and rivers, and its abundance in marine sediments is considered to be an indicator of fire intensity in the region from which it originated. These recorded burning events appear most likely to represent periods of highly variable climate with fuel loads built up during wet periods being subsequently burnt during drier periods. Even for the most recent peaks, an anthropogenic origin cannot be unequivocally established.

In the same vein, the synthesis by Moore et al. (2022) considered three deep-water sites off West Africa and showed a distinct latitudinal relationship between past changes in rainfall and fire activity over the last 50,000 years. In particular, at the southernmost site (9°N, off the Guinean forest), i.e. the most tropical, fire activity decreased during intervals of increasing humidity, while the northernmost site (21°N, off the Saharan Desert) clearly demonstrates the opposite relationship. It is concluded that, well before the Holocene, fire activity was suppressed by low fuel loads exerting the dominant control on burning in the tropics of northern Africa. Moreover, the lack of an increase in charcoal fluxes in the youngest part of the records (Late Holocene) and the relationship between aridity and fire activity argues against human activity as the key control on charcoal fluxes.

To distinguish natural from anthropogenic fires, the consensus is the coexistence of artefacts with wood charcoal collected from the same deposits. Nevertheless, by using reflectance, natural and some anthropogenic fire events can be distinguished with more confidence (Belcher et al., 2018; Scott, 2018); the higher the temperature reached, the higher the reflectance is. As a result, reflectance can potentially discriminate wood charcoal from land clearance or natural fires from lightning strikes reaching temperatures between 405–450°C (e.g. Scott, 2018) – from charcoal obtained from pottery production (600–800°C, e.g. Gosselain, 2002) – or charcoal from iron smelting activities (1000°C and greater, e.g. Bocoum, 2004). However, this method has not (yet) been applied to Central Africa (Clist et al., 2023).

The chronostratigraphic limits of this review will be constrained by the available studies, with priority given to potential human interactions and environmental impacts with an emphasis on Holocene deposits and, more particularly, those of the last three millennia.

2. Palaeoenvironmental reconstruction of fires during the Holocene

2.1. Global perspective

Globally, the Holocene is recognized as the period of increasing human population densification, even if it is a rather irregular and unequal process depending on the regions of the world. Likewise, across the Holocene, fire regimes have changed as recorded from quantitative reconstructions of biomass burning using stratified charcoal records.

According to Carcaillet et al. (2002), to understand the origin of palaeofires, the main challenge is to distinguish between climatic drivers, vegetation changes, and possible human impacts. Nevertheless, Sweeney et al. (2022) have shown that quantitative analysis of charcoal can be used throughout most continents to identify the first stages of the intensification of fire activity in relation to increasing human populations. In Europe, a significant increase in fire activity is dated 6000 cal BP, whereas in northeastern North America, it was greatest before 7500 cal BP, very low between 7500–3000 cal BP, and has been increasing during the last 3000 years. In the Amazon basin and in Central America, the greatest burning occurred during the middle Holocene. Only during the last 2000 years did burning increase again in the Amazon basin with high human densities (e.g. de Souza et al., 2018).

During the Holocene in Europe, it is generally accepted that anthropogenic burning was initiated or maintained open landscapes as populations grew more rapidly (e.g. Gobet et al., 2003; Kaal et al., 2011; Vannière et al., 2016; Dietze et al., 2018). However, on the Iberian Peninsula, there is no consistent correlation between rapid changes in the rate of population growth and the increased occurrence of fires across the Neolithic period (Sweeney et al., 2022), suggesting limited human influence on fire regimes during the period between 10,000 and 3500 cal BP. Such limited correlation may be due to the introduction of agriculture not being a single event, as the start of the Neolithic was asynchronous. Indeed, evidence suggests that agriculture was established initially in the south and east of the peninsula, and spread from there, with the earliest evidence of farming in the northwestern part of the region dating to around 6000 cal BP. In spite of these trends, the analysis shows that increases in fire precede periods of rapid population growth by several centuries, which is more difficult to explain, suggesting other drivers, such as climate and climate-induced environmental changes, may have been more significant influences at generating fires during this period.

2.2. Western African tropical forest overview

Sweeney et al. (2022) acknowledge that the African continent, especially the tropical part, has not been the target of sufficiently precise studies to provide a conclusive evaluation regarding palaeofires. Bremond et al. (2024) found that quality data were lacking to reconstruct a robust trend in biomass burning before 5000 years ago at the African continental scale. Compared to the Iberian Peninsula, the quantitative reconstructions of Holocene vegetation characteristics for tropical Africa (especially in the rainforest) have limited spatial coverage or temporal resolution, while focusing also on only a restricted range of vegetation types (Maley et al., 2019).

In the African tropical rainforest, charcoal deposits are widespread, though not ubiquitous. Thus, for example, in the inhospitable interfluvial peatland in the central Congo Basin, no clear evidence for anthropogenic activity has been found yet, though abundant charcoal dates back to the Pleistocene period of the record, and probably reflects natural rather than anthropogenic fires due to the very low density of hunter-gatherers throughout the Quaternary (Hawthorne et al., 2023).

Indeed, marked human impact on fire regimes of evergreen forest in Africa is considered unlikely before 40,000–4000 yr ago. A major anthropogenic impact on fire activity identified at several sites ca. 4000 yr ago is similarly unlikely as this is before the use of fire for large-scale

land clearance and agropastoralism (Archibald et al., 2012). Even if some authors still consider the possible role of early human fire starters, palaeoenvironmental syntheses emphasize above all that climatic forcing is the main driver (Willis et al., 2013). Past vegetation changes in response to warmer and drier climates in Africa were therefore often nonlinear, highly variable spatially and appear to have been dependent on specific ecosystem resilience to aridity at the local and regional scales.

A recurring point of weakness remains the uncertain estimation of human population densities in African tropical forests, a parameter better documented on other continents and often essential in the explanation of fire regimes (Pausas and Fernandez-Muñoz, 2012; Cardoso et al., 2018; Dietze et al., 2018; Blarquez et al., 2018). Furthermore, these sedimentary charcoal studies, like other palaeoenvironmental proxies, are often analysed separately from archaeological studies (Lupo et al., 2015).

The empirical evidence for anthropogenic impact has been gathered recently at the regional Central African scale (Clist et al., 2023). It has revealed that after a low level of Stone Age activity from ca. 40,000 to 3000 cal BP, the “Iron Age” followed with pottery-producing communities, often recorded in association with a slowly increasing number of wood charcoal occurrences and dating since ca. 3200–3000 cal BP (Fig. 3). The peak of recovered and dated anthropogenic wood charcoal occurs between ca. 2300–1600 cal BP. At the “provincial” level, the timing of the end of the Stone Age-associated charcoal, and the “Iron Age” material with its high charcoal abundance varies slightly between the areas considered (Clist et al., 2023).

T 19

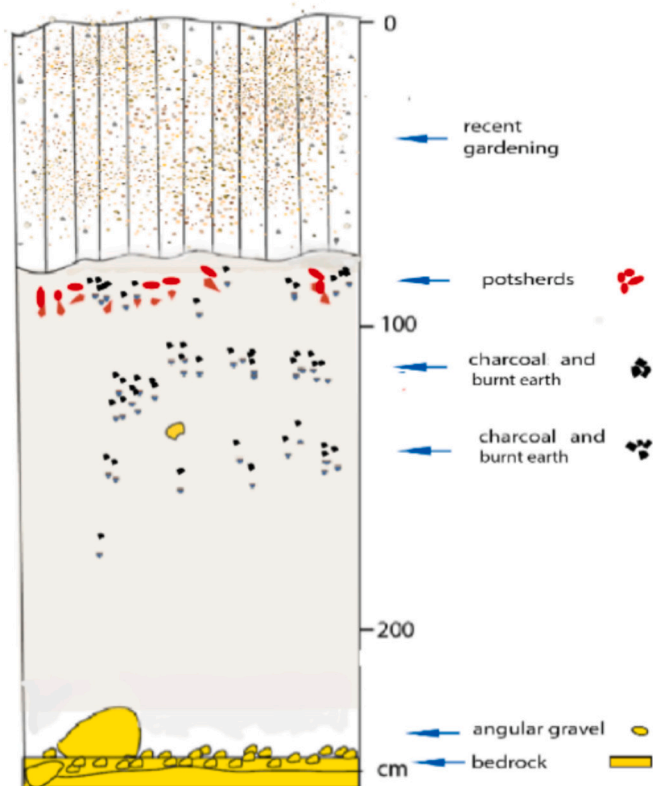


Fig. 3. Gombe, trench 19, typical soil profile (redrawn from Cahen, 1976). The soil profile of the Gombe site is composed of an underlying bedrock whose top is covered by rounded pebbles. Above the bedrock, an overlying sandy mantle of 3 to 5 m occurs (Moeyersons, 1978). The upper part of the sands, apart from Tshitoliian artefacts, contained pottery of various styles (Cahen, 1976, 1978a, 1978b), associated with charcoal; other charcoal was observed between 100 and 200 cm soil depth.

Botanical analysis of charcoal, from the southernmost boundary of the Mayombe forest, indicated the taxa used as fuelwood between 1200 and 700 cal BP (Hubau et al., 2013, 2014, 2015). However, the composition of taxa reflects the surrounding environment (mature rainforest with patches of regenerating forest and open vegetation types) and seems unbiased by human activity (see Section 4.4 and Fig. 7).

The upper soil layers in Cameroon contain a mixture of both recent and ancient charcoal which could reflect several mechanical reworking episodes (Vleminckx et al., 2014), as observed in previous ^{14}C date distributions from other Central African countries (Brncic et al., 2007, 2009; Hubau et al., 2013). Thus, it cannot be assessed whether this correlation indicates that slash-and-burn agriculture was concentrated in the same places over the last centuries and ca. 2000 years ago.

In SE and SW Cameroon, charcoal remains were found in each study area, revealing frequent and widespread past forest fires occurring during two very distinct periods – one from ca. 80 to 850 cal BP (on average 300 years old) and another from ca. 1500 to 2800 cal BP (on average 1900 years old), and referred to respectively as “recent” and “ancient” charcoal (Vleminckx et al., 2014). In neighbouring northern Congo, a similar situation was described from twelve sites, where wood charcoal starts to appear from c. 1100 cal BP with a sharp increase from 500 cal BP (Tovar et al., 2014); the fact that the documented fires are asynchronous and without any spatial correlation indicates they were likely anthropogenic.

In northern Congo, fire and climate change impacts on the composition of lowland rainforest were analysed (Brncic et al., 2007, 2009), where at the seasonally-flooded swamps of Mopo Bai and Goulougo, charcoal concentrations increased after ca. 1200 and ca. 600 cal BP, respectively, and attributed to anthropogenic activities.

3. Methodological approach limits

One approach for disentangling the presence/absence of human habitation is by investigating charred botanical remains (charcoal and endocarps) recovered during palaeoenvironmental studies in order to distinguish between forest slash-and-burn practices, rather than natural fires. Nevertheless, despite the central role that fire has played in shaping many modern ecosystems, there remains little information on how early anthropogenic burning may have begun and significantly affected natural fire regimes.

Although less frequent, fires are possible even under the relatively humid conditions that characterized most of the Holocene in tropical Africa (Tutin et al., 1996). Assessments of microscopic charcoal from pollen slides remain uncommon, despite the importance of fire activity in forest disturbance dynamics. Another difficulty is linked to fire-return intervals in tropical savanna and in disturbed forests that are generally shorter (between 1 and 10 years) than in temperate or cold systems (Archibald et al., 2010). Aleman et al. (2013) considered the timing and scale of natural or anthropogenic fires in African rainforests, noting that charcoal records are strongly linked to local vegetation cover and land use patterns. As such, forest fires occurred mostly near the boundaries with savannas, while forest encroachment of savanna was widespread. Indeed, simulations showed that the observed transitions could not have produced the current biome distributions. Elsewhere, across the Ngotto Forest, Central African Republic (CAR), sedimentary charcoal records indicate that Holocene fire activity is limited by climatically-driven modulation of precipitation regimes (Kiahtipes, 2016, 2019).

Several recent studies on charcoal dispersal, particularly on the European and North American continents, are trying to refine methodologies in order to better understand the palaeoenvironmental significance of measurements. Charcoal particle distribution and deposition are strongly influenced not only by energy release rates, but also by particle size, density and shape. Hence, small differences in the shape and density of grass and wood charcoal particles can induce marked differences in dispersal from the source area. Notably, the dispersal of wood charcoal shows a localized deposition signal which decays with

distance, while grass charcoal shows a more diffuse deposition lacking a localized centre, for both particles $>125\mu\text{m}$ and $>60\mu\text{m}$ (Vachula and Richter, 2018; Vachula and Rehn, 2022).

3.1. Charcoal measurements

A concern is to be able to differentiate the (proximal) impacts of local conditions from (distal) broadscale patterns in the data (Marlon et al., 2008; Daniau et al., 2010). As such, Vachula et al. (2018) have provided transport scales for the processes: macroscopic charcoal may represent short transport ($<1\text{ km}$), whereas mesoscopic charcoal ($63\text{--}150\mu\text{m}$) appears to be a reliable proxy up to 150 km . While the strength of fire studies is their common use for spatially-distributed sample plots, they do not employ a shared method for charcoal quantification and identification. Usually, microscopic charcoal fragments ($>10\mu\text{m}$) were quantified at the time of pollen counting using the pollen-slide method (Clark, 1988); they represent regional fire activity and can express wind or runoff transport. Kiahtipes (2016) used assessments of microcharcoal size distribution, and charred grass cuticle concentrations to argue for a brief phase of forest disturbance along the lower Lobaye River (CAR). Elsewhere, a study from the savanna landscape of South Africa quantified the transport areas of carbonaceous particles according to their size (Duffin et al., 2008). This investigation revealed that lake deposits contained particles of up to $200\mu\text{m}$ in size transported from source areas of $0\text{ to }5\text{ km}$, while smaller particles originated from up to $10\text{ to }15\text{ km}$ away. Macroscopic charcoal fragments ($>125\mu\text{m}$) were extracted by sieving, bleaching and disaggregation (Hawthorne et al., 2018), and corresponded to short distance transport and local fire activity, i.e. *in situ* combustion. In the same way, charcoal particles $>150\mu\text{m}$ were monitored yearly using traps submerged in lakes from boreal forest landscapes in eastern Canada (Hennebelle et al., 2020). The particle dispersal process indicated mostly wind transport within the regional ($<30\text{ km}$) source area. Even if these high-quality methodological studies have not yet been carried out in tropical Africa, it should be noted that existing macrocharcoal deposits can provide a reliable proxy for reconstructing past burned areas and severity of fires.

3.2. Bioturbation and pedoturbation incidences

Bioturbation contributes to moving and mixing charcoal within the soil profile that was originally lying in the topsoil (Carcailliet and Talon, 1996). In temperate areas (e.g. Alsace, northeastern France), Schwartz and Gebhardt (2011) described, from a 1 m depth sandy soil profile, several charcoal layers of approximately the same age (about 2000 years old). This was due to bioturbation by worms, causing the soil to become strictly homogeneous in terms of particle-size. These conclusions can equally apply to intertropical regions where biological activity is particularly rapid. This phenomenon has been examined by McBrearty (1990), where termites are especially abundant, and able to bring material from several metres depth up to the surface, creating great amounts of loose material. Subsequently, their mounds are easily eroded once abandoned, thus feeding the colluvium and resultant mixing (Freysinet et al., 1990; Roquin et al., 1991; Boulet et al., 1995). Such processes most likely result in the scattering of charcoal after a single forest fire event, rather than being due to successive fire events (Schwartz, 2014).

In considering the vertical distribution of ancient charcoal, Vleminckx et al. (2014) observed that the absence of any age-depth relationship might be due to soil profile pedoturbation caused by biotic or abiotic agents. The main biotic agents in tropical soils are termites and ants, but earthworms, rodents, wind-fallen trees or tree uprooting can also play a role. However, abiotic factors, such as steep slopes can particularly exacerbate the erosion of colluvium in tropical conditions. Nevertheless, archaeologists, often observe layers of charcoal interbedded with artefacts in profiles occurring over several metres thickness, without any interruption or obvious traces of post-depositional

disturbance. Thus, this can indicate the possible existence of micro-areas in the soil devoid of strong bioturbation (e.g. Peyrot et al., 1990; Clist, 1995; Coutros et al., 2024).

3.3. Fires and biomass characteristics

Only a few studies are available covering tropical or subtropical regions, in either open or closed ecosystems (e.g. Duffin et al., 2008). The greatest concern is the lack of knowledge of how fire frequency and/or intensity vary across different vegetation types and climatic regimes. In southern Cameroon, tree species were classified in regeneration guilds (pioneer, non-pioneer light-demanding, shade-tolerant) and characterized by their wood specific gravity, assumed to reflect light requirements (Vleminckx et al., 2014). A positive correlation was expected between the relative abundance of light-demanding species and charcoal abundance in the upper soil layer. However, this study did not yield any evidence that the current heterogeneity in tree species composition can be explained by charcoal abundance in any soil layer. Instead, the fires are strongly associated with biomass characterised by Cyperaceae and Poaceae, suggesting that fuel type may have been important in determining the fire regime, although fuel load and moisture typically also play a role in igniting fires (McLauchlan et al., 2020).

Recent charcoal records from lake sediments in the Central African Republic were compared in three ecosystems (forest, savanna, and forest-savanna mosaic) with land cover inferred from remote-sensing images (Aleman et al., 2013). Charcoal accumulation rates were combined with charcoal width-to-length ratios and mean charcoal size in order to investigate the land-use history of the landscapes surrounding the study sites. However, in the same lakes, it was noted that mean charcoal size could be affected if riparian forest acted as a physical filter to charcoal accumulation.

4. Case studies illustrating important ancient movements of wood charcoal in various soil types from open-air sites in Central Africa

4.1. Pointe Gombe in the DRC

Pointe Gombe, also known as Pointe Kalina, is situated inside Kinshasa, the capital of the Democratic Republic of Congo. It was first excavated by J. Colette between late 1925 and 1927, with the results published later (Bequaert, 1938). Due to important aspects relating to the stone industries of Central Africa, D. Cahen opened new exposures in 1973 and 1974 (Cahen, 1976). Details of the excavation results can be found in a series of papers (Cahen, 1978a, 1978b, 1981; Cahen et al., 1983). The focus here is the evidence of wood charcoal and artefacts having been subjected to important lateral, and especially vertical movements (Moeyersons, 1978; Cahen and Moeyersons, 1977; Cahen et al., 1983).

The soil profile of the Gombe site comprises a sandy mantle of $3\text{ to }5\text{ m}$ thickness overlying bedrock, whose top is covered by rounded pebbles. On the bedrock were found a few possible Acheulean tools, followed by (moving up to the surface) Lupemban, Sangoan and Tshitoliian toolkits (Fig. 3). The upper part of the sands, besides Tshitoliian artefacts, contained pottery of various styles (Cahen, 1976, 1978b). A total of 28 radiocarbon and thermoluminescence dates were obtained from various depths and features in the sands (Cahen et al., 1983; Fig. 4), revealing several chronological inversions and reworking.

The evidence for this is demonstrated by some lithic artefacts separated by up to 1 m , yet originating from the same knapped block (Fig. 5). Furthermore, examining the dates since $50,000\text{ cal BP}$ at the site level reveals the results are too widespread, suggesting that wood charcoal was reworked in the same way as the lithics (Cahen et al., 1983). Moeyersons tried to explain this dispersion (Cahen and Moeyersons, 1977; Moeyersons, 1978), and concluded also that termites and worms bring up material from various depths to the surface, while gaps created

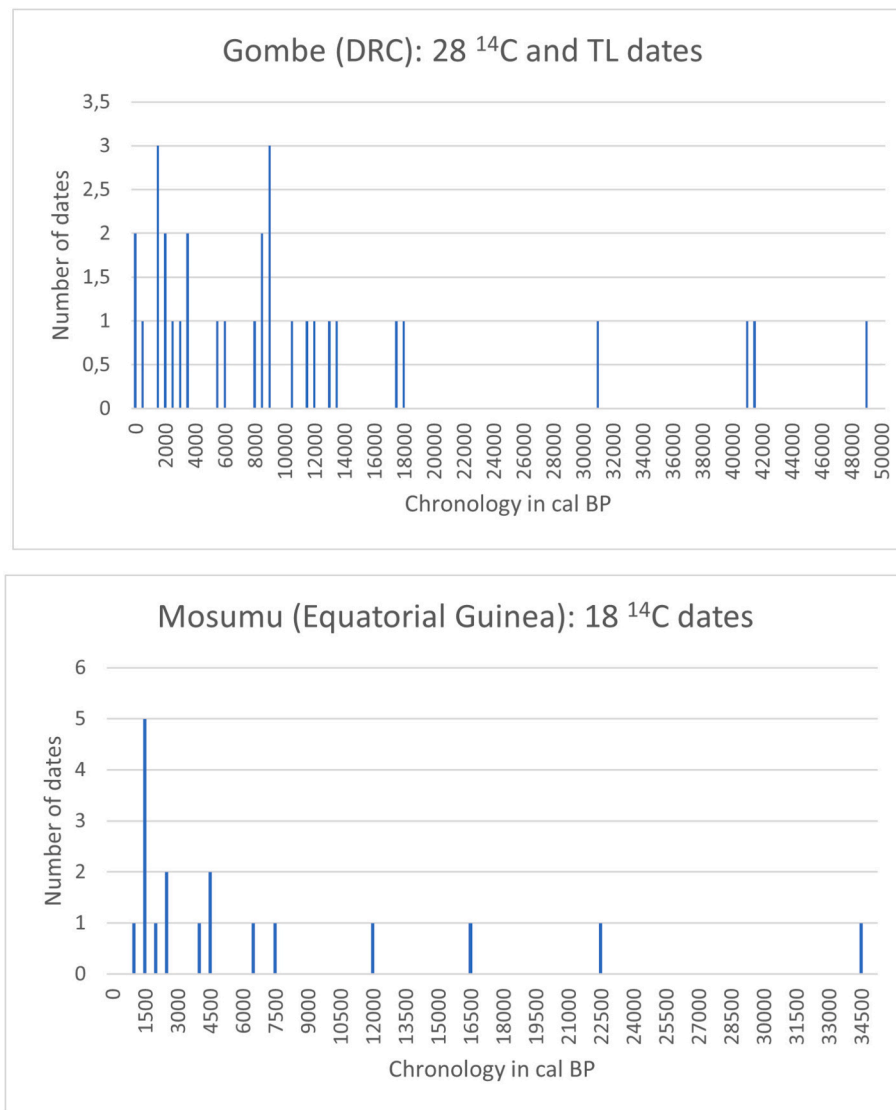


Fig. 4. The wide distribution of the 28 ¹⁴C and TL dates from Gombe (DRC) and of the 18 ¹⁴C assays from Mosumu (Equatorial Guinea) (Figures created using the data from [Clist et al., 2023](#)).

allow material to move down.

4.2. Stone lines and Mosumu in Equatorial Guinea

Palaeolithic assemblages are frequently associated with layers of gravel of varying thickness known as “stone lines”, which are widespread Quaternary features appearing in tropical and subtropical regions around the world. In the African wet tropics, stone lines are a prevalent feature ([Vincent, 1966a, 1966b](#); [Rünge, 2001](#); [Peyrot et al., 2003](#)). Their deposition consists in many cases of only one “line”, but several superimposed “lines” can be observed (e.g. [Lanfranchi and Schwartz, 1990](#); [Rünge, 2001](#); [Mercader et al., 2002](#)). Despite considerable lateral variation, they are commonly comprised of three superposed deposits: (i) a basal saprolite derived from the weathering of the basement; (ii) an intermediate blocky horizon, looking like a polygenous, chaotic breccia known as the Stone Line (s.s.); and (iii) a sandy to clayey upper layer usually designated as a “ferralsol” – this cover horizon is frequently absent in areas of marked relief.

The Stone Line (s.s.) thickness is less than 1 m and varies laterally, while the co-occurrence of a well-preserved lithic industry is abundantly documented ([Lanfranchi, 1990](#); [Locko, 1991](#); [Schwartz, 1996](#); [Mercader et al., 2002](#)). However, archaeological deposition and stone-line

configuration may be unrelated to geological events separated by thousands of years. Consequently, the imbrication of archaeological materials with stone-lines and the distribution of these materials remain questionable ([Moyersons, 1987](#); [McBrearty, 1990](#); [Johnson, 1993](#)).

The cover horizon is a homogeneous blanket covering the landscape, and more usually interpreted as a colluvial (hill wash) deposit. This interpretation implies that the sandy to clayey materials of which it is composed originate from the upper parts of the relief and are spread along the slopes by water transport (e.g. see [Fig. 3](#)). Fine carbon fragments intimately inserted in the mass of the sandy and clayey matrix are present at all levels giving the opportunity to perform ¹⁴C dating.

The site of Mosumu, in the tropical rainforest of continental Equatorial Guinea, yielded Middle and Later Stone Age assemblages that were dated to at least the last 30,000 years ([Mercader et al., 2002](#)). Middle Stone Age artefacts were found in Layer I at 2 m–1.5 m depth, while Later Stone Age material was recovered in Layer II, buried between the surface and 1.5 m depth ([Mercader and Marti, 2003](#)). The 18 charcoal samples from which the AMS radiometric ages were obtained came from the lowermost, middle and uppermost part of the “stone-line”, thus associated with the site’s Layer I, as illustrated in several profiles ([Mercader et al., 2002](#)). The wood charcoal sizes range between 0.5 and 1 mm, and exceptionally up to 2 mm. The radiocarbon-dated

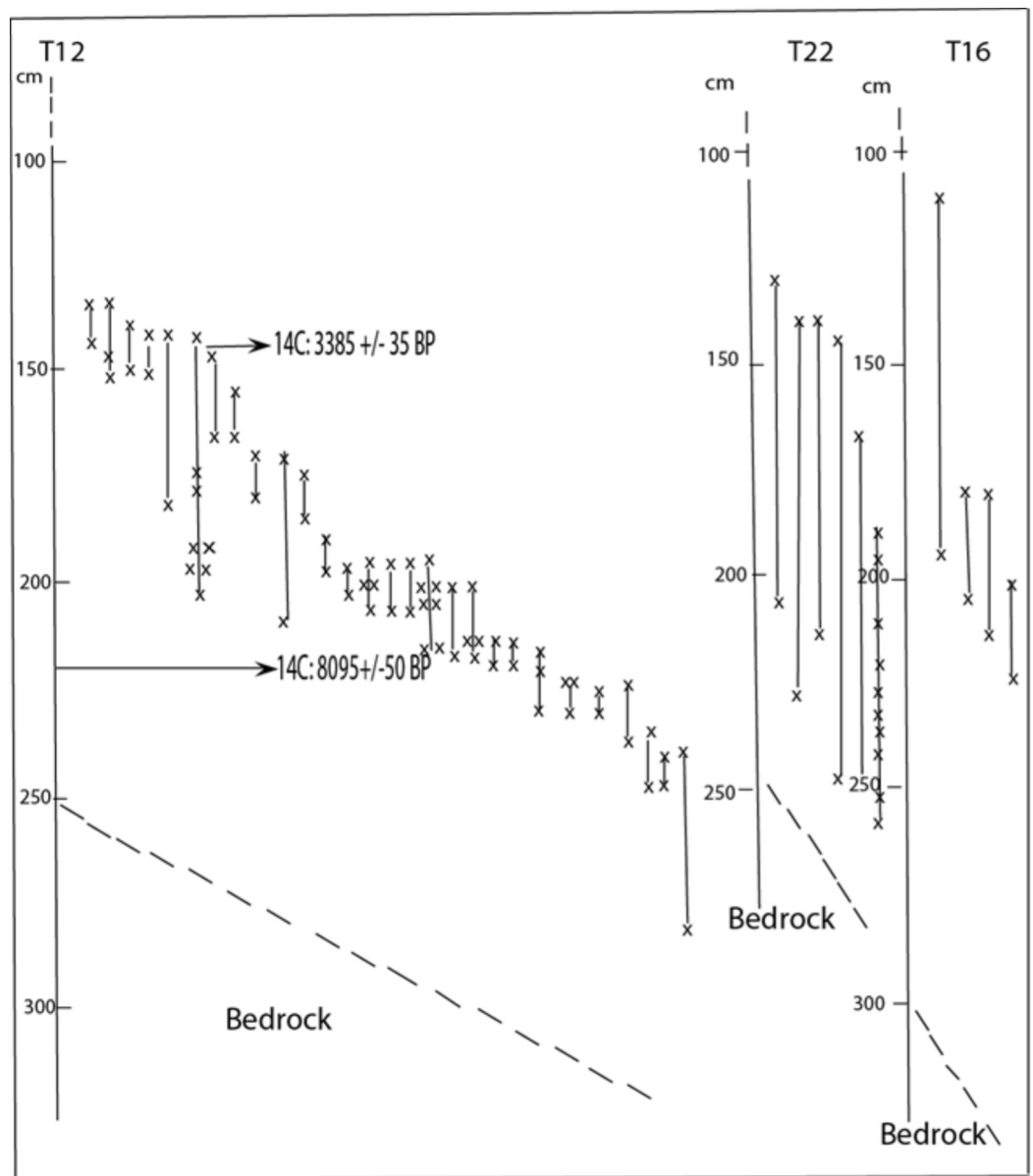


Fig. 5. Gombe – vertical distribution of conjoined lithics from trench nos. 12, 22 and 16 (after Cahen et al., 1983).

lithics of Layer I are recorded as dispersed vertically along a maximum thickness of 80 cm (Marti Lezana, 2003). None of the ^{14}C dates provide a coherent picture: the seven dated charcoal samples from the basal part of the Stone Line range from 1545 to 22,940 cal BP; the eight from the middle part of the Stone Line extend from 1709 to 34,662 cal BP; and lastly the three from the upper part of the Stone Line range from 1486 to 2227 cal BP. Other known excavated and dated Later Stone Age sites, e. g. in Gabon, are younger than 10,000 cal BP with artefacts found in the upper half of the covering soil (Clist, 1995), i.e. from the same position as at Mosumu. Marti Lezana (2003) carried out some limited examination of the associated lithic artefacts from Layer I, and though few in number, maximum movements were recorded in the horizontal plane of 1.07 m and 0.3 m in the vertical plane. The latter figure is surprising considering the obvious movement of the dated charcoal and the results from Gombe in the DRC (see Figs. 4–5).

4.3. Chronology and depositional processes of the cover horizon

It has been suggested that the cover horizon was renewed by aeolian

deposition during the Holocene and probably since 3000 cal BP (Thiéblemont, 2013). Subsequently, this was linked to an environmental crisis, ca. 2500–2000 cal BP, and it was argued, based on evidence collected in Gabon, that the cover horizon lying above the Stone-Line is relatively homogeneous from a particle-size perspective and incompatible with biological activity. Consequently, this cover horizon appeared to correspond to aeolian deposition rather than a soil horizon. Supporting this argument, the Central African forest would have almost completely disappeared between 3000 and 2000 cal BP, and perhaps even as early as 4000 cal BP. Such conclusions have been the matter of a lively debate of two opposing arguments:

1. A major perturbation occurred during the third millennium BP (Maley et al., 2019; Giresse et al., 2020). This was marked by an abrupt decrease of many forest taxa, linked at the same time to a significant, rapid extension of pioneer-type forest vegetation. Subsequently, a denuded surface as assumed by Thiéblemont (2013) is impossible. Many lacustrine deposits have been investigated in Cameroon, Gabon and Congo, but no aeolian deposits were recognized, except the Saharan diatom flux in Lake Ossa (Nguetsop et al., 2004).

2. Reworking of the ground by termites or worms leads to the homogenization of particle-size fractions, although a slow increase in the clay fraction with depth is often observed in the case of sandy soils. As a consequence, bioturbation also leads to the reworking in sequences of coarse elements originally lying on the topsoil. Such reworking is frequent for charcoal (Carcaillet and Talon, 1996), but also for archaeological artefacts. Furthermore, Thiéblemont (2013) described the occurrence of several charcoal layers having approximately the same age (about 2000 years old) in a 1 m depth profile. Meanwhile, the particle-size composition of soil horizons overlaying the stone-lines is highly variable in Central Africa, and reflects the composition of the parent material, i.e. these deposits are not typical of aeolian landforms, which are completely lacking in Central Africa.

Lastly, and not discussed at the time, most of the wood charcoal deposits from Gabon found in the cover horizon were associated with archaeological remains (Clist, 2006; Clist et al., 2018). Around the Gabon Estuary, it has been shown that charcoal from the bottom of the cape dates back to ca. 43,000 cal BP. Through the sandy-clay deposit up to the surface, occurs a regular chronological gradient from the Late Pleistocene to the Late Holocene and modern times (Clist, 1995; Clist et al., 2023). Likewise, the Lopé reserve sector in central Gabon has a very similar chronology for the sandy-clay mantle (Peyrot et al., 2003). Thus, the chronology suggested by Thiéblemont (2013) cannot be accepted; the existing cover horizon started to be deposited during the late Pleistocene and the position of buried dated wood charcoal illustrates more recent episodes.

4.4. Taxa composition of charcoal from the southern Mayombe forest reflect the surrounding environment without human selection

The Lukula site is located on the southern edge of the Mayombe forest, north of the Congo River. The trench excavated to 1.6 m depth provided a profile from which wood charcoal, pottery and iron slag were collected, and dated to around 1000 cal BP (Hubau et al., 2014). The assessment of pedoanthracological assemblages and taxonomic identifications at Lukula provides a detailed view of past fire regimes and vegetation changes (Hubau et al., 2014, 2015). Taking into account that pollen is generally poorly preserved at archaeological sites in the region, this study offers one of the rare examples of a stratigraphic study in

tropical forests. Here, the charcoal is systematically evaluated with regard to the botanical spectrum deduced from the identified charcoal debris and the distribution of artefacts (pottery fragments and iron slag). The assemblage is composed of at least 30 different taxa (genus level), which correspond to savanna species, long- and short-lived pioneers and mature rainforest species. It is thus possible to reconstruct the major charcoal assemblages: evergreen rainforest species, regenerating rainforest species, margin forest-savanna species and woodland savanna species. These are divided up in terms of specific components: high trees, small trees and shrub savanna species, long- and short-lived pioneer species, and mature rainforest species (Fig. 6).

As noted already, the information from terrestrial charcoal archives is geographically restricted, allowing the possibility of tracing the zonal vegetation of a local (small) area, in contrast to pollen analysis which gives assemblages resulting frequently from long-distance transport.

Soil thin sections show abundant micro-tunnels and associated features indicating strong bioturbation throughout the profile. Bioturbation can explain both the strong vertical scatter of artefacts and some ^{14}C date discrepancies. Scattered fragments of charcoal, iron slag and pottery may have been moved deeper down in the soil profile due to human passage in an initial phase, and soil disturbance in a second phase. Radiocarbon dates indicate that the assemblage was formed over a restricted period of some 400 years, between 1143 and 717 cal BP (Fig. 6).

The simultaneous presence of mature rainforest taxa, pioneers, secondary forest taxa, woodland savanna taxa and taxa with wide ecological tolerances indicate that as today no particular forest type was preferred for fuelwood gathering. This is in agreement with current species preferences. Similarly, there was no preference for particular heavy or light types of wood. Furthermore, calorific value measurements of the taxa selected cover a broad range ($18.52\text{--}20.33\text{ MJ kg}^{-1}$) confirming that calorific values do not vary much in tropical woods and are of minor importance for fuelwood selection by local communities (Abbot et al., 1997; Eberhard, 1990). Conclusively, a wide variety of activities, such as cooking, heating, iron smelting, pottery production or fuel burning for ceremonial or medicinal purposes can be considered for this Lukula charcoal assemblage site.

In such conditions, it is possible that the assemblage formed over a relatively long period rather than during one specific event. It is thus

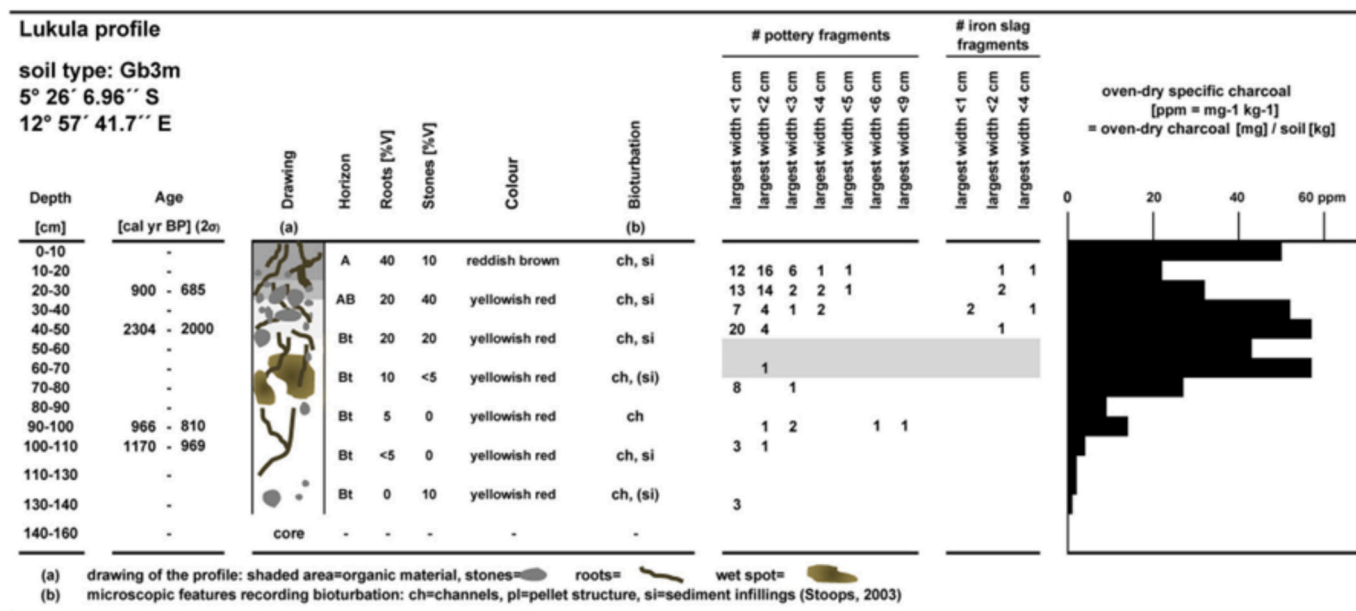


Fig. 6. Profile description and distribution of artefacts (pottery fragments and iron slag) and charcoal throughout the Lukula profile. The grey shade in the pottery fragments and iron slag columns indicates an artefact-free interval (50–70 cm) separating two distinctly different artefact assemblages (after Hubau et al., 2014; Stoops, 2003).

envisaged that the Lukula assemblage constitutes a “synthetic” deposit of scattered charcoal fragments, resulting from long-term deposition. This charcoal assemblage is representative of the vegetation surrounding the Lukula community between 1200 and 700 cal BP: the presence of different vegetation types suggests a rather fragmented landscape. In contrast to current forest-savanna mosaics, fragmentation around 1000 cal BP cannot be explained exclusively by human activity. Fragmentation may have been partly caused by a climatic event coinciding with the Medieval Climate Anomaly (MCA), as evidence for its impact on palaeoclimatic conditions in Central Africa is increasing (Fig. 7).

Profile description and distribution of artefacts (pottery fragments and iron slag) are compared with charcoal deposits throughout the profile. Their abundance makes it possible to distinguish horizons linked to human activity from those where biological or mechanical perturbation occurred subsequently. In this Mayombe forest example, bioturbation can explain both the strong vertical scatter of artefacts and the ^{14}C date discrepancies. This palaeoenvironmental history would thus benefit in the future from textural analyses, associated with microscopic observations of the nature of abiotic particles, in order to recognize the continuity or discontinuity of the accumulation and, possibly, the distal or proximal sources of the material.

It was concluded that the primary control on fire activity in the forest zone is climatic in origin, but cannot fully reveal the possible role of humans: “As such, taxa composition of charcoal is not biased by human selection, suggesting it reflects the surrounding environment that was characterised by mature rainforest with patches of regenerating forest and open vegetation types”. As there is no other evidence for the occurrence of an earlier occupation level in this area, the older charcoal fragments are likely to be the result of a natural forest fire in the vicinity of the profile site between 2300 and 2000 cal BP. A charcoal assemblage of the same age has also been reported from the Ituri Forest (DRC) (Hart et al., 1996).

Charcoal identifications indicate that mature rainforest patches did persist through these successive crises, until 800 cal BP. After 800 cal BP, the dominance of pioneer and woodland savanna taxa indicates that rainforest regeneration was hampered by increasingly severe drought conditions. The steep and densely forested slopes of the southern edge of the Mayombe forest might have discouraged early migrants. Furthermore, settlers prefer clearing soft pioneer trees instead of the denser and harder mature rainforest trees (Neumann et al., 2012; Hubau et al., 2014). Therefore, they were probably more attracted by fragmented areas with a higher abundance of regenerating forest, such as at forest edges. This could perhaps explain the absence of any artefacts in the profiles, which are located in the heart of the southern Mayombe forest. Charcoal from these profiles is likely of natural origin, indicating natural fire occurrences linked to drought events.

4.5. People–tree interactions and fuelwood management among slash-and-burn Fang and Benga societies of Equatorial Guinea

An investigation was carried out on how wood is chosen and collected by two separate but neighbouring Bantu-speaking peoples from Equatorial Guinea (Picornell-Gelabert et al., 2011; Picornell-Gelabert, 2020): the Fang on the continent, and the Benga who settled on Mandji Island, i.e. before ending as wood charcoal and becoming part of the archaeological record.

The Fang study, mainly ethno-sociological in nature, defines the area of the garden peripheral to the homes which increases radially as the village expands due to the daily cutting of trees and shrubs in order to provide fuelwood. Such a process implies that the fuelwood comes from close to the village and that, for simple convenience, there was no need to travel further. Fang people collect fuelwood indiscriminately, the most important criteria being log diameter and ease of collection rather than botanical species. However, they recognize “good fuels” as dense and hard woods that burn slowly and do not produce too much smoke. The Fang, like other slash-and-burn societies in tropical environments,

maintain a topocentric organization of space (Fig. 8). Consequently, this choice of catchment areas restricts botanical information to the immediate clearing zones: fuelwood is always obtained from trees growing in socialized spaces (tsií, ekot, mbut) and never from the more distant rainforest (afán), where the spirits of plants, animals and ancestors may dwell.

In cases where large quantities of fuelwood are required, old gardens can be exploited based on the most dried out wood available, with larger diameters of trunks and branches chosen for long-lasting fires. Combustion and cooking residues are collected and generally accumulated between banana plants, which need fertilizing. In addition, men can cut wood selected for their magical or medicinal properties, but the quantities concerning this categorization generally remain modest; they may also protect several species providing sacred wood.

As documented for the Fang, the Benga inhabiting Mandji Island (also known as Corisco Island) do not select particular tree species for their fuelwood supply (Picornell-Gelabert, 2020). They have an extensive knowledge of the properties of each species and a shared perception of what is good fuel according to their domestic fuel needs (dense, dry hardwood with a proper diameter). However, this “good fuel” criterion does not apply to the household supply of fuelwood, as all of the wood left after land clearance is collected. As noted in other ethno-archaeological studies (e.g. Picornell-Gelabert et al., 2011; Dufraisse et al., 2005; Henry and Thiéry-Parizot, 2014), botanical species are not a ubiquitous criterion used in fuel selection. All of those interviewed agreed that they would use fuelwood from the orchards and along paths within secondary-growth forest and fallow lands, rather than make an extra trip to collect fuelwood elsewhere. There are also fruit-bearing trees, occasionally supplying naturally fallen branches as fuelwood, but overall, the preponderance is non-selection of fuelwood species as observed among the neighbouring Fang people.

The main take-away message of Picornell-Gelabert’s work is that the wood charcoal found in archaeological excavations from Fang or Benga settlements will often not be coming from the primary forest, but from secondary vegetation associated with clearance and maintaining orchards. The creation of new cultivated lands means cutting down the forest and burning the fallen wood, and thus inserting typical wood charcoal into the earth.

5. Research approaches and discussion

5.1. Central African rainforest fires are believed to be primarily human-driven?

There is fairly rich documentation regarding human impacts on the environment towards the end of the African Humid Period. Humans are not passive agents, and can be viewed as active agents in broad-scale landscape denudation (Wright, 2017). These studies are located outside or on the border margins of the Central African forest area. However, their well-established conclusions could provide a model to be cautiously adapted to the forest environment.

Within the Central African forest, several studies (e.g. Kiahtipes et al., 2011; Kiahtipes, 2019) sought to characterize anthropogenic impact in Africa’s rainforests, but the lack of evidence restricts the ability to measure the influence of prehistoric populations on forest composition. These investigations refer to several palaeoenvironmental studies suggesting the ecological influence of past societies, while ignoring the majority of works concluding that this influence does not exist. For example, it is considered that the anomalous sedimentation rates at Lake Tizong (Cameroon) after 1000 cal BP may be the result of erosion linked to anthropogenic impacts, yet no direct links were established with the pollen results (Lebamba et al., 2016). Similar conclusions for the last millennium were proposed about Lake Bambili in Cameroon (Stager and Anfang-Sutter, 1999; Lézine et al., 2013).

Likewise, late Holocene pollen, microcharcoal and geochemical data were analysed from Mopo Bai (Brncic et al., 2009) and Goulougo

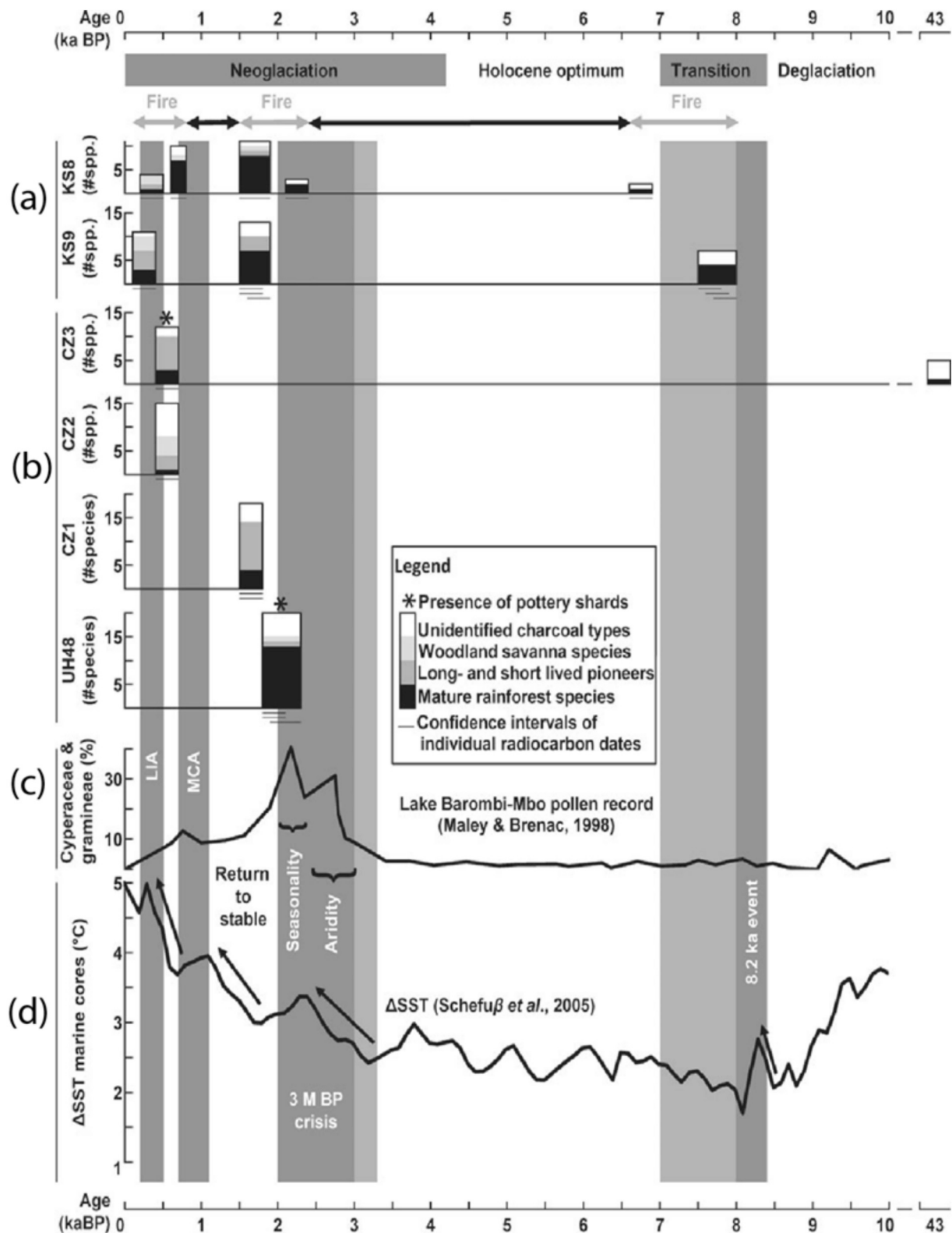


Fig. 7. Charcoal-inferred palaeofire occurrence and vegetation composition of the heart (a) and the edge (b) of the Mayumbe forest, with other selected vegetation (c) and climate (d) records. The three main disturbance periods are indicated with grey bands: 8.2 ka BP event, the third millennium BP crisis (see the text), Medieval Climate Anomaly (MCA) and Little Ice Age (LIA). (a) Overview of the composition of charcoal assemblages formed during wildfires in the Kisala Singa area. Shades of colour represent vegetation types: black: mature rainforest; dark grey: regenerating forest; light grey: woodland savanna; white: unidentified types. All dates are given in calendar years before present, with the present set at 1950 AD. The lines just under the bars represent the 2 σ confidence intervals after calibration for each of the individual radiocarbon dates obtained in that charcoal assemblage. (b) Overview of the composition of charcoal assemblages formed during wildfires in the Luki reserve. Bar width represents the 2 σ confidence interval after calibration. (c) Abundance of savanna and hygrophilous species (Cyperaceae and Gramineae) in the Barombi-Mbo pollen record (Maley and Brenac, 1998). (d) ΔSST = 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 ΔSST (Figure after Hubau et al., 2015).

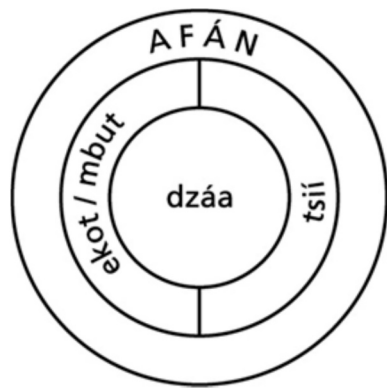


Fig. 8. Fang topocentric organization of space, in which the village (dzáa), the centre of social activity, is separated from the primary forest (afán) by other social spaces – orchards (tsif) and fallow lands (ekot/mbut) (after Picornell-Gelabert et al., 2011). The scale of this diagram is not indicated by the authors, though it would be of the order of a few hundred metres.

(Brncic et al., 2007), in the northern Congo area, where at both sites, persistent heliophilic formations and increasing microscopic charcoal concentrations were recorded during the last 1200 years. These data collectively were tentatively interpreted to indicate human activity, but without independent archaeological evidence being provided.

Elsewhere, charcoal influxes in sediment cores from a range of forest types in the Republic of Congo indicated no major increase in fire activity at ca. 2500 cal BP, but a pronounced shift only after 1100 cal BP (Tovar et al., 2014). Concluding that fire is an important factor shaping vegetation cover, these authors suggested that the Late Iron Age agriculturalist populations might be linked to important changes in the frequency of these fires.

In the eastern Congo Basin (Ituri Forest), Hart (2001) reported that charcoal identification showed little change in forest composition during the last 4000 cal BP and suggested that many of these ignitions were anthropogenic, while drier climatic regimes permitted these fires to become more widespread. In fact, forest fires are more numerous because they are easier to start when the landscape is more open.

From the Lopé Reserve in Gabon, sedimentary charcoal provided evidence of mature, heliophilic, and open woodland vegetation dating to between 1800 and 1700 cal BP (Oslisly and White, 2007). These authors considered that anthropogenic maintenance of vegetation mosaics is linked with slash-and-burn agriculture, and suggested that there exists a distinction between the climatically-driven onset of forest fragmentation across the Atlantic Central African forest zone and the human activities maintaining vegetation mosaics. However, as underlined by Kiahtipes (2019), they offered no recommendations for how to differentiate between these two suggested controls.

In a similar hypothetical way, it has been suggested from the palynological record of Lake Ossa (Cameroon) that Bantu settlement after 2000 cal BP was responsible for maintaining vegetation mosaic formations, which appeared after climatically-driven extension of the dry season during the onset of the Late Holocene (Reynaud-Farrera et al., 1996).

On the other hand, and in a more convincing way, human intervention is evoked on the scale of the last few centuries in the proximity of several areas of mining activities. Thus, near the Central African Republic border with the Republic of Congo, Kiahtipes (2016) and Lupo et al. (2015), using fossil pollen, microcharcoal and $\delta^{12}\text{C}/^{13}\text{C}$, concluded that very localized but marked forest impacts were driven by fuel production for iron smelting after ca. 400 cal BP.

In line with the key-findings of the present study, we consider that the forest fragmentation recorded was primarily driven by climate change.

5.2. Rainforest fires are believed to be mainly driven by climatic control?

Fairhead and Leach (1998) argue that the selective use of hardwood species for charcoal in the past would not necessarily have produced widespread deforestation.

Detailed charcoal assemblage studies and taxonomic identification in the southern Mayombe forest (DRC) were previously summarized (Hubau et al., 2013, 2014; see Section 4.4). As noted, these investigations argue that the primary control on fire activity in the forest zone between 1200 and 700 cal BP is climatic in origin and cannot fully reveal the possible role of humans. As there is no other evidence for the occurrence of an earlier occupation level in this area, the older charcoal fragments in the same profile are likely to be the result of natural forest fires in the vicinity of the site between 2300 and 2000 cal BP.

In the same Mayombe Forest, a pedoanthracological approach investigated forest perturbation in the last few centuries at the Yoko Reserve using subsoil Marantaceae disturbance indicators (Mbayu et al., 2016). The fossil charcoal originates either from slash-and-burn agriculture or from household fires. It is only more recently, since ca. 600 yr ago, that *Gilbertiodendron dewevrei* trees have been notably burned in this area (Tshibamba Mukendi et al., 2014). Comparing charcoal identifications with forest inventory data showed that the monodominant Limbali forests were sometimes converted to other forest types such as open-canopy Marantaceae forests. The forest transformation could have been partly driven by heavier anthropogenic pressure, as potsherds were sometimes associated with the charcoal fragments.

Unlike the origin of present-day forest-savanna mosaics from human activity, fragmentation around 1000 cal BP may have been provoked by a well-known climatic event coinciding with the Medieval Climate Anomaly, which undoubtedly had a significant impact on Central African forest composition (Giresse et al., 2023). The presence of different vegetation types suggests a rather fragmented landscape. In contrast to current forest-savanna mosaics, an exclusive human explanation cannot clarify forest fragmentation around 1000 cal BP. Furthermore, Tshibamba Mukendi et al. (2014) consider that Late Holocene fires are likely tied with Iron Age agriculturalists settling and maintaining mosaic environments established during past arid anomalies. However, the settlement of this ancient community does not appear to be associated with the practices of large-scale slash and burn. The charcoal taxa identified belong either to mature rainforest, pioneer forest, regenerating forest or woodland savanna, indicating that ancient and current local populations gathered fuelwood in several different forest types.

Another potentially informative source for discerning burning in the vicinity of human settlements is the occurrence of both charred grass cuticles and wood. Indeed, the few traces of charcoal encountered rather suggest intermittent natural fires (Giresse et al., 1994).

In Central Africa, previous examination of the sandy fractions of Holocene lake sediments, after washing, did not reveal coarse and sufficiently concentrated charcoal to indicate intense burning associated with clearance (Giresse et al., 2020, 2023). However, some clues can be recalled from other sites. Concerning Lake Barombi Mbo, on the volcanic Cameroon Line, the palynological, sedimentological and geochemical evidence indicates that forest disturbance (ca. 2600 cal BP) is climatic in origin, with the absence of human occupation evidence on the shores and slopes supporting this conclusion (Giresse et al., 1994, 2018; Maley and Brenac, 1998).

The Shum-Laka rock shelter in Cameroon provides a continuous record of lithic industries throughout the Late Pleistocene and Early Holocene (Cornelissen, 2003). Despite the evidence of long-term occupation, a strong human imprint on palaeofires is not notable. The lack of an increase in charcoal fluxes in the Late Holocene part of the records and the clear relationship between aridity and fire activity argue against human activity as the key control on charcoal fluxes. Fires triggered by human activity only became dominant over natural events during the last few millennia or even centuries.

Located a short distance from the edge of the forest ecosystem,

several sites provide evidence of forest retreat over the past few millennia. In northeast Nigeria, the past vegetation of Lake Tilla was analysed by [Salzmann et al. \(2002\)](#). They concluded that the anthropogenic origin hypothesis of Sudanian savannas during the Holocene should be rejected. The constancy of the charcoal curve provides no evidence whether these fires were mainly of natural origin or induced by early hunters, who may have started them long before the onset of the Holocene. Similarly, in the Dahomey Gap, where a broad savanna corridor interrupts the West African rainforest zone, the palaeorecords from Lake Sélé indicate that the shaping of the corridor was related to large-scale climatic changes in which the role of humans has been previously overestimated ([Salzmann and Hoelzmann, 2005](#); [Bremont et al., 2017](#)).

Given the small amount of evidence available from the western part of the Central African forest, the information here is necessarily supplemented from a little further east.

Metal-using agriculturalists spread gradually into Eastern Africa, resulting in the greatest landscape alterations by around 1500 cal BP ([Schoenbrun, 1998](#)). Random or discontinuous fire occurrences may represent isolated human-made fires. However, the authors acknowledge that pollen indicators for such changes have remained elusive ([Beuning, 1999](#); [Marchant et al., 2018](#)), while the resolution used is too coarse to identify human modifications to ecosystems.

A reliable 17,000-year record of biomass burning in the Lake Victoria area, on the Indian Ocean side of Africa, shows patterns that can possibly be transposed to the Atlantic side of the African continent ([Temoltzin-Loranca et al., 2023](#)). At around 8000–6000 cal BP, a decline in burning was likely caused by warm and moist conditions. More precisely, the fire regime shift was accelerated by the reduced flammability of rainforest vegetation and positive feedbacks in moisture availability ([Ivory and Russell, 2016](#)). Continuous sedimentary charcoal assessment combined with new pollen records suggest that before human impact increased during the Iron Age (ca. 2400 cal BP), biomass burning decreased significantly when the rainforest expanded in response to increasing temperatures and moisture availability ([Colombaroli et al., 2018](#)).

5.3. Charcoal in the Central African rainforest and causation issues

One of the sources of confusion in the comments with the often-assumed anthropogenic origin of charcoal could be linked to ecosystems that burn. In the savanna, human-caused fires can regulate the rhythms of natural fires and reduce their size and frequency, whereas in the forest, natural fires are rare and anthropogenic action will be more significant on the ecosystem ([Haldon, 2018](#)).

Much of the transitional zone between the Guineo-Congolian rainforest and the Sahel is hypothesized to be the product of anthropogenic impact through cultivation and fire ([White, 1983](#)). Less numerous are those studies concerning strictly forest or savanna blocks ([Kiahtipes, 2019](#)). However, these forest blocks are not homogeneous, but consisting of varied vegetation likely to evolve over time in response to the fluctuating climatic and environmental changes.

Fires and charcoal often frame the question of anthropogenic impact being the primary cause of clearly defined environmental changes. This simplification appears as unrealistic because nature is itself defined by articulated dynamic processes operating at different geographical and chronological scales, including human behaviour and culture ([Coddington and Bird, 2015](#); [Kiahtipes, 2019](#)). Subsequently, the ecological influences of past societies should be analysed within the broader envelope of climate change. However, this view seems to ignore the fact that in early Holocene times, human densities were very low and that many records suggest the strong preponderance of climatic factors, with human action being viewed as an uncertain hypothesis.

The incidence of human intervention in the rainforests of West and Central Africa appears all the more speculative, although this was the period when the first stages of Bantu migration occurred towards the south. These populations, especially itinerant, corresponded to only low

densities and, the available evidence seems to indicate that very large areas remained practically uninhabited. Some rare quantitative data have been provided in Gabon ([Clist, 1995](#)): for the “Neolithic” (from ca. 2000 to 0 BC), an occupation density of 0.2 inhabitants per km² was estimated during reconnaissance fieldwork in the Ngounié forest, whereas in the Iron Age (ca. 400 BC until the end of the 15th century), an average of 0.5 inhabitants per km² could be estimated, i.e. approximately 134,000 inhabitants.

On the Batéké Plateau, the first iron smelting industry did not appear until the beginning of the first millennium CE, i.e. several centuries after the first metallurgical wave in Central Africa. [Pinçon \(1990, 1991\)](#) calculates that, even at the sites where iron concentrations were the densest, the supply of fuelwood could be easily achieved only by the biomass of the few surrounding forests, i.e. without inducing a significant forest decline. Thus, in this scenario, the iron industry cannot be held responsible for the appearance of vast savanna areas, as production was restricted near the iron ore deposits (here ferrallitic soils).

In the Ngotto Reserve, mirroring the stable carbon isotope record, the charcoal data also suggest stable, but heterogeneous forest formations occurring in multiple stages of ecological succession ([Kiahtipes, 2016](#)). Overall, there is limited indication of local fire activity, and the available data indicate natural processes driving the conversion of forests to savanna-woodlands.

A global history of humans and society, as introduced by [Degroot et al. \(2021\)](#), does not systematically consider the impact of humans on the environment as we tend to do on the African continent, but more the influence of climate on the history of society. The authors note that various studies assume a too linear relationship between the severity of past weather and the recorded magnitude of societal disasters. Such caution applies *a fortiori* to the palaeoenvironments of the Central African rainforest and to its fire regime causalities. As such, social and environmental datasets here are not of comparable quality and resolution, and may therefore simply assume causation between changes that appear coeval in connecting large-scale climatic trends to local weather events.

Although [Archibald \(2016\)](#) analysed exhaustively the number and size of fires, fire intensity, fire frequency and seasonality in African grassy ecosystems, unfortunately forest burning was insufficiently investigated as it was assumed to be less significant. However, an important direct impact of humans on fire is in changing the timing of ignition events. Lightning shows strong seasonality and is the only significant source of ignitions in the absence of people: it usually occurs with rainfall during thunderstorms and is virtually non-existent in the dry season. Human ignitions are not similarly constrained, and currently in Africa the number of fires peak when there is no lightning in the middle of the dry season.

In the past few centuries, a strong negative correlation exists between population density and the total area burned, implying that as population numbers increased in Africa, the extent of fires has declined ([Archibald et al., 2009, 2016](#)). It was suggested that the colonial past was overall a period when fires were fought and banned, and thus that the area burned currently in Africa is probably lower than it has been for the previous several thousand years ([Marlon et al., 2008](#)).

5.4. Resilience of Central African rainforests

The climatic and human histories of the three major tropical forest areas of the planet, Central Africa, Southeast Asia, and Amazonia/Central America are very different. In their simulation of the resilience of tropical rainforests to climate change, [Huntingford et al. \(2013\)](#) carried out a systematic exploration of CO₂-induced emissions scenarios for all three main tropical forest regions and considered that the largest uncertainties are associated with plant physiological responses, followed by future emissions scenarios. Although they concluded evidence of forest resilience for all three regions, one of the simulations revealed that the tropical forests of the Americas are projected to lose biomass by

the end of the twenty-first century. Indeed, since this study, the combination of sustained droughts, deforestation and human-ignited fires in Amazonia are questioning whether tipping points have already been exceeded, with some areas less resilient to rainforest dieback due to small decreases in precipitation (Flores et al., 2024).

Other differences in resilience of these three regions seem notably linked to the contrasting early influences of humans and subsequent processes. Fletcher et al. (2021) reviewed tropical ecosystems in tropical south and southeast Asia, and South America, respectively. In the former, biodiversity was enhanced by the introduction of swidden agriculture, while in the latter, domestication of over 80 crop species occurred, with traditional management practices thought to have played an important role in shaping the structure and resilience of forests, as well as maintaining diverse ecosystem services. However, due to lack of data, this assessment, did not take into account the African continent.

Nevertheless, concerning tropical Asia, Zheng et al. (2021) assessed the decisive broad-scale ecological implications of the expansion of rice agriculture around 2,000 yr ago. This led not only to widespread deforestation, but also had lasting impacts on forest biodiversity (Roberts et al., 2021). Likewise, in Amazonia, using charcoal and crop data together, it is inferred that human occupation has occurred for more than 8000 years (Bush et al., 2007), which is at least twice as old as Central Africa. Increasing evidence is also revealing the scale at which people influenced Amazonian forest composition (including using fires) to promote useful and edible species, and creating in some areas “built environments”, with large population centres, mostly close to the river networks (e.g. Levis et al., 2018; Maezumi et al., 2022). This is up until the arrival of European diseases in the 1500s causing massive indigenous depopulation, with the forests rapidly growing back until recent exploitation and clearance.

However, an attempt at a comparative analysis of Central African forest history with its low human densities and those of tropical Asia and the Amazon remains limited when we consider respectively the marked agrarian expansion of rice cultivation around 2000 BP and the large-scale pre-Columbian human occupation.

With Copernicus confirming that 2024 is the first year to exceed 1.5°C above pre-industrial levels, this ongoing trend is likely to undermine the resilience of tropical rainforests, particularly Amazonia. However, modelling of elevated CO₂ levels and faster forest growth rates may offset some of the impacts of more frequent and intense extreme climate events, according to Yao et al. (2024). Nevertheless, according to the latest “State of Wildfires 2024–2025” (Kelley et al., 2025), there is a growing evidence base that greenhouse warming is making extreme wildfires more likely and more severe around the world. The fire season saw notable spikes in the tropical forest of the Congo basin, where it was reported that “fire weather was 3–8 times more likely with climate change, with a 2.7-fold increase in burnt area”.

Finally, in terms of African rainforests remaining resilient, it is not just about climate change or human impacts causing fragmentation and opening up the canopy, thus facilitating more frequent fires. One also needs to consider the important roles that seed dispersers, pollinators, mycorrhizal networks and soil seed banks play in maintaining and restoring forests (e.g. Corrales et al., 2018; Giresse et al., 2020; Adjalla et al., 2022).

6. Conclusions

1. In early Holocene times, human densities were very low, suggesting that human degradation of tropical African rainforests should be viewed as an uncertain hypothesis. Then, in late Holocene times, the first stages of Bantu migration occurred towards the south. These populations, especially itinerant, corresponded also to only low densities and, in spite of some evidence of temporary camps leading to the first villages, very extensive areas remained largely uninhabited, as clearly shown in Gabon for the “Neolithic” and the Iron Age.

2. Historical reconstruction of the African rainforest offers a growing number of examples of resilience that distinguish it from other tropical forests on the South American and Asian continents which were exposed to marked physical influences of human colonization. Differences in the resilience of these three wet tropical forests seem notably linked to the contrasting early influences of humans and subsequent processes. However, more inhabitants do not necessarily mean greater environmental degradation as shown, for example, by sustainable management practices in pre-Columbian Amazonia.

3. Central African rainforests thus constitute an original example of recording CO₂-induced climate change. The vast amounts of carbon stored in the Congo basin’s peatland forests mean that they are of global importance in the fight against climate change (Carcaillet et al., 2002), with a history of peat formation reconstructed from the late Pleistocene to the present day (Hawthorne et al., 2023).

It is suggested that autogenic succession and variation in the amount and seasonality of precipitation have been the most important drivers of ecological change in this peatland. No conclusive evidence for anthropogenic activity was provided here; charcoal influx rates are high throughout the Pleistocene part of the record and may reflect natural rather than anthropogenic fires. The open Pleistocene landscape is likely to have been easier to access for humans, but to date, there is little information on the nature and density of these hypothetical populations.

4. Fires and charcoal debris frequently frame the question of anthropogenic impact being the primary cause of clearly defined environmental changes. This oversimplification appears as unrealistic because nature is itself controlled by dynamic processes developing at different geographical and chronological scales including human behaviour and culture.

From the perspective of conditions favourable to the repetition of natural fires in dry grass-sedge vegetation during the dry season(s), recent climatic data from space observations (Christian et al., 2003) and from present day lightning activity (Soula et al., 2016) reveal the Congo Basin as one of the most lightning-prone regions on Earth. Its activity is primarily associated with violent phenomena such as thunderstorms and convective rains which require regional sources of humidity, such as from the swampy forests in the central part of the Congo Basin and also the lakes close to the Great Rift Valley (Victoria, Edward, Kivu).

The recent increase in lightning activity in Central Africa, mainly in the Congo Basin, could result from some kind of solar influence, as has been suggested for causing forest fragmentation between ca. 2500 and 2000 cal yr BP (Maley et al., 2019).

5. In the meantime, current anthropogenic impacts in the form of massive deforestation, combined with burning to provide land for industrial agriculture, across the tropics continue to contribute to both local and global emissions. As such, the consequences and tipping points are unpredictable for both the local and global climate, and could be amplified, especially if the accumulating tropical peat deposits no longer act as sinks, dry out and become vulnerable to fires.

CRedit authorship contribution statement

Pierre Giresse: Writing – original draft, Conceptualization. **Bernard Clist:** Writing – original draft, Conceptualization. **Alex Chepstow-Lusty:** Writing – review & editing. **Jean Maley:** Writing – original draft.

Declaration of competing interest

This is to confirm that the 4 authors of this paper: Pierre Giresse, Bernard Clist, Alex Chepstow-Lusty and Jean Maley have no conflicts of interest in submitting their review article – *Ancient charcoal archives for understanding palaeofire regimes, sedimentary processes and vegetation changes in the rainforests of Central Africa: review and challenges*

Acknowledgements

We are very grateful to the comments of the two anonymous reviewers and the editor, Fabienne Marret-Davies who helped us greatly improve our review and widen our perspective. The study has been almost continuous over the last few decades. PG and JM benefited from several forms of official support, but also from many friendly relations, in particular with our Congolese, Gabonese and Cameroonian colleagues. We acknowledge here particularly the two main programmes that have most deeply and lengthily supported the progress of our research, both in the field and in the laboratory: the ECOFIT program (Ecosystems and Palaeoecosystems of the Intertropical Forests) funded by CNRS and ORSTOM (now IRD) and the CAMPUS program funded by the French Ministry of Cooperation (today part of the Ministry for Europe and Foreign Affairs). BC has benefited over the years from strong interactions with colleagues from the AfricaTervueren Museum, the Brussels and Gent Universities in Belgium, the ORSTOM-Pointe-Noire and Brazzaville laboratories in Congo, the National Omar Bongo University and the National Herbarium in Gabon, and the Institute for National Museums in the Democratic Republic of Congo.

Data availability

The authors confirm that all data necessary for supporting the scientific findings of this paper have been provided.

References

- Abbot, P., Lowore, J., Khofi, C., Werren, M., 1997. Defining firewood quality: a comparison of quantitative and rapid appraisal techniques to evaluate firewood species from a southern African savanna. *Biomass Bioenergy* 12, 429–437.
- Adjalla, C., Tosso, F., Salako, K.V., Assogbadjo, A.E., 2022. Soil seed bank characteristics along a gradient of past human disturbances in a tropical semi-deciduous forest: Insights for forest management. *For. Ecol. Manag.* 503, 119744.
- Aleman, J.C., Blarquez, O., Bentaleb, I., Bonté, P., Brossier, B., Carcaillet, C., Gond, V., Gourlet-Fleury, S., Kpolita, A., Lefèvre, I., Oslisly, R., Power, M.J., Yongo, O., Bremond, L., Favier, C., 2013. Tracking land-cover changes with sedimentary charcoal in the Afrotropics. *The Holocene* 23 (12), 1853–1862. <https://doi.org/10.1177/0959683613508159>.
- Archibald, S., 2016. Managing the human component of fire regimes: lessons from Africa. *Philos. Trans. R. Soc. B* 371, 20150346. <https://doi.org/10.1098/rstb.2015.0346>.
- Archibald, S., Roy, D.P., van Wilgen, B.W., Scholes, R.J., 2009. What limits fire? An examination of drivers of burnt area in Southern Africa. *Glob. Chang. Biol.* 15, 613–630. <https://doi.org/10.1111/j.1365-2486.2008.01754>.
- Archibald, S., Nickless, A., Govender, N., et al., 2010. Climate and the inter annual variability of fire in southern Africa: A meta analysis using long term field data and satellite derived burnt area data. *Glob. Ecol. Biogeogr.* 19, 794–809.
- Archibald, S., Staver, A.C., Levin, S.A., 2012. Evolution of human-driven fire regimes in Africa. *Proc. Natl. Acad. Sci. USA* 109 (3), 847–852. <https://doi.org/10.1073/pnas.1118648109>.
- Belcher, C.M., New, S.L., Santín, C., Doerr, S.H., Dewhurst, R.A., Grosvenor, M.J., Hudspeth, V.A., 2018. What can charcoal reflectance tell us about energy release in wildfires and the properties of pyrogenic carbon? *Front. Earth Sci.* 6, 169.
- Bequaert, M., 1938. Les fouilles de Jean Colette à Kalina. *Ann. Mus. Congo Belge, série 1, Anthropologie et Préhistoire, Tervuren* 1, 2.
- Beuning, K.R.M., 1999. A re-evaluation of the late glacial and early Holocene vegetation history of the Lake Victoria region, East Africa. In: van Zinderen Bakker, E.M., Heine, K. (Eds.), *Palaeoecol. Africa and the Surrounding Islands*. Routledge, pp. 115–136.
- Bird, M.I., Cali, J.A., 1998. A million-year record of fire in sub-Saharan Africa. *Nature* 394 (6695), 767.
- Bird, M.I., Cali, J.A., 2002. A revised high-resolution oxygen-isotope chronology for ODP- 668B: implications for Quaternary biomass burning in Africa. *Glob. Planet. Chang.* 33 (1–2), 73–76.
- Blarquez, O., Talbot, J., Paillard, J., Lapointe-Elmrabti, L., Pelletier, N., Gates St-Pierre, C., 2018. Late Holocene influence of societies on the fire regime in southern Québec temperate forests. *Quat. Sci. Rev.* 180 (15), 63–74.
- Bocoum, H., 2004. The origins of iron metallurgy in Africa: new light on its antiquity; West and Central Africa. *Memory of peoples*, 30, 240 p., ISBN : 978-92-3-103807-5, 92-3-103807-9.
- Boulet, R., Pessenda, L.C.R., Telles, E.C.C., Melfi, A.J., 1995. Une évaluation de la vitesse de l'accumulation superficielle de matière par la faune du sol à partir de la datation des charbons de bois et de l'humine du sol. Exemple des latosols des versants du lac Campestre, Salitre, Minas Gerais, Brésil. *CR Acad. Sci. Paris* 320 (lia), 287–294.
- Bremond, L., Bodin, S.C., Bentaleb, I., Favier, C., Canal, S., 2017. Past tree cover of the Congo Basin recovered by phytoliths and $\delta^{13}C$ along soil profiles. *Quat. Int.* 434, 91–101.
- Bremond, L., Aleman, J.C., Favier, C., Blarquez, O., Colombaroli, D., Connor, S.E., Cordova, C.E., Courtney-Mustaphi, C., Dabengwa, A.N., Gil-Romera, G., Gosling, W. D., Hamilton, T., Montade, V., Andriantsilavo, H.I., Razafimanantsoa, L., Mitchell, J., Power, J., Razanatsoa, E., Yabi, I., Vannière, B., GPD contributors, 2024. Past fire dynamics in sub-Saharan Africa during the last 25,000 years: Climate change and increasing human impacts. *Quat. Int.* 711, 49–58.
- Brncic, T.M., Willis, K.J., Harris, D.J., Washington, R., 2007. Culture or climate? The relative influences of past processes on the composition of the lowland Congo rainforest. *Phil. Trans. Royal Soc. Biol. Sci.* 362, 229–242.
- Brncic, T.M., Willis, K.J., Harris, D.J., Telfer, W.M., Bailey, R.M., 2009. Fire and climate change impacts on lowland forest composition in northern Congo during the last 2580 years from palaeoecological analyses of a seasonally flooded swamp. *The Holocene* 19 (1), 79–89.
- Bush, M.B., Silman, M.R., De Toledo, M.B., Listopad, C., Gosling, W.D., Williams, C., De Oliveira, P.E., Krisel, C., 2007. Holocene fire and occupation in Amazonia: records from two lake districts. *Philos. Transact. R. Soc. B Biol. Sci.* 362 (1478), 209–218.
- Cahen, D., 1976. Nouvelles fouilles à la pointe de la Gombe (ex-pointe de Kalina), Kinshasa. *Zaire. L'Anthropologie* 80 (4), 573–602.
- Cahen, D., 1978a. New excavations at Gombe (ex Kalina) point. Kinshasa, Zaire, *Antiquity*, pp. 51–56.
- Cahen, D., 1978b. Vers une révision de la nomenclature des industries préhistoriques de l'Afrique Centrale. *L'Anthropologie* 82 (1), 5–36.
- Cahen, D., 1981. Contribution à la chronologie de l'âge du fer dans la région de Kinshasa (Zaire). In: *Préhistoire africaine, mélanges offerts au Doyen Lionel Balout. A.D.P.F, Paris*, pp. 127–137.
- Cahen, D., Moeyersons, J., 1977. Subsurface movements of stone artefacts and their implications for the prehistory of Central Africa. *Nature* 266, 812–815.
- Cahen, D., Moeyersons, J., Mook, W.G., 1983. Radiocarbon dates from Gombe point (Kinshasa, Zaire) and their implications. In: Mook, W.G., Waterbolk, H.T. (Eds.), *Proceedings of the first international symposium: 14C and archaeology, Groningen 1981. Conseil de l'Europe, Strasbourg*, pp. 441–452.
- Carcaillet, C., Talon, B., 1996. Aspects taphonomiques de la stratigraphie et de la datation de charbons de bois dans les sols: exemple de quelques sols des Alpes. *Géog. Phys. Quatern.* 50, 233–244.
- Carcaillet, C., Almquist, H., Asnong, H., et al., 2002. Holocene biomass burning and global dynamics of the carbon cycle. *Chemosphere* 49 (8), 845–863.
- Cardoso, A.W., Oliveras, I., Abernethy, K.A., Jeffery, K.J., Lehman, D., Ndong, J.E., McGregor, I., Belcher, C.M., Bond, W.J., Yadavinder, Y.S., 2018. Grass species flammability, not biomass drives changes in fire behavior at tropical forest-savanna transitions. *Front. For. Glob. Change* 1, 6. <https://doi.org/10.3389/ffgc.2018.00006>.
- Christian, H.J., Blakeslee, R.J., Boccippio, D.J., Boeck, W.L., Buechler, D.E., Driscoll, K. T., Goodman, S.J., Hall, J.M., Koshak, W.J., Mach, D.M., Stewart, M.F., 2003. Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res. Atmosph.* 108 (D1). <https://doi.org/10.1029/2002JD002347> pp. ACL-4.
- Clark, J.S., 1988. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. *Quat. Res.* 30, 67–80.
- Clist, B., 1995. Gabon: 100 000 ans d'Histoire. *Centre Culturel Français Saint-Exupéry (Libreville, Gabon), Sepia*, p. 376.
- Clist, B., 2006. Mise en évidence dans le nord-ouest du Gabon de la présence de l'homme au sein des forêts d'âge Holocène. *J. Afr. Archaeol.* 4 (1), 143–152.
- Clist, B., Bostoen, K., de Maret, P., Eggert, M.K.H., Höhn, A., Mbida Mindzie, C., Neumann, K., Seidensticker, D., 2018. Did human activity really trigger the late Holocene rainforest crisis in Central Africa? *Proc. Natl. Acad. Sci. USA* 115 (21), E4733–E4734. <https://doi.org/10.1073/pnas.1805247115>.
- Clist, B., Béarez, P., Mougne, C., Lesur, J., Hubau, W., Bostoen, K., 2023. First archaeological excavations along the Atlantic Ocean coastline of the Democratic Republic of Congo: The Iron Age sites at Muanda. *Afr. Archaeol. Rev.* 40 (4), 711–739.
- Cochrane, M.A., 2003. Fire science for rainforests. *Nature* 421, 913–919.
- Codding, B.F., Bird, D.W., 2015. Behavioral ecology and the future of archaeological science. *J. Archaeol. Sci.* 56, 9–20.
- Colombaroli, D., van der Plas, G., Rucina, S., Verschuren, D., 2018. Determinants of savanna-fire dynamics in the eastern Lake Victoria catchment (western Kenya) during the last 1200 years. *Quat. Int.* 488, 67–80. <https://doi.org/10.1016/J.QUAINT.2016.06.028>.
- Cornelissen, E., 2003. On microlithic quartz industries at the end of the Pleistocene in Central Africa: The evidence from Shum Laka (NW Cameroon). *Afr. Archaeol. Rev.* 20, 1–24. <https://doi.org/10.1023/A:1022830321377>.
- Corrales, A., Henkel, T.W., Smith, M.E., 2018. Ectomycorrhizal associations in the tropics –biogeography, diversity patterns and ecosystem roles. *New Phytol.* 220 (4), 1076–1091.
- Coutros, P.R., Matonda, I., Doman, J.H., Pachiarotti, S., Mesfin, I., Bostoen, K., 2024. The beginning of the Iron Age south of the Congo rainforest: the first archaeological investigations around Idiofa (Congo), c. 146 BC–AD 1648. *Azania: Archaeol. Res. Africa* 59 (2), 213–248.
- Daniau, A.L., Harrison, S.P., Bartlein, P.J., 2010. Fire regimes during the last glacial. *Quat. Sci. Rev.* 29, 2918–2930.
- de Souza, J.G., Schaan, D.P., Robinson, M., et al., 2018. Pre-Columbian earth-builders settled along the entire southern rim of the Amazon. *Nat. Commun.* 9, 1125. <https://doi.org/10.1038/s41467-018-03510-7>.
- Degroot, D., Anchukaitis, K., Bauch, M., Burnham, J., Carnegie, F., Cui, J., de Luna, K., Guzowski, P., Hambrecht, G., Huhtamaa, H., Izdebski, A., Kleemann, K.,

- Moesswilde, E., Neupane, N., Newfield, T., Pei, Q., Xoplaki, E., Zappia, N., 2021. Towards a rigorous understanding of societal responses to climate change. *Nature* 539–550. <https://doi.org/10.1038/s41586-021-03190-2>.
- Dietze, E., Theuerkauf, M., Bloom, K., Brauer, A., Dörfler, W., Feeser, I., Feurdean, A., Gedminiene, L., Giesecke, T., Jahns, S., Karpinska-Kolaczek, M., Kolaczek, P., Lamentowicz, M., Latalowa, M., Marcisz, K., Obremaska, M., Pedziszewska, A., Poska, A., Rehfeld, K., Stancikaite, M., Stivrins, N., Swieta-Musznicka, J., Szal, M., Vassiljev, J., Veski, S., Wacnik, A., Weisbrodt, D., Wiethold, J., Vannière, B., Słowinski, M., 2018. Holocene fire activity during low-natural flammability periods reveals scale-dependent cultural human-fire relationships in Europe. *Quat. Sci. Rev.* 201, 44–56. <https://doi.org/10.1016/j.quascirev.2018.10.005>.
- Duffin, K., Gillson, L., Willis, K., 2008. Testing the sensitivity of charcoal as an indicator of fire events in savanna environments: Quantitative predictions of fire proximity, area and intensity. *The Holocene* 18, 279–291.
- Dufraisie, A., Pétrequin, A.M., Pétrequin, P., 2007. La gestion du bois de feu: un indicateur des contextes socio-écologiques. Approche ethnoarchéologique dans les Hautes Terres de Papua (Nouvelle Guinée indonésienne). M. Besse (ed.) Sociétés néolithiques. Des faits archéologiques aux fonctionnements socio économiques. Actes du 27e colloque interrégional sur le Néolithique (Neuchâtel, octobre 2005), Lausanne. Cahiers d'archéologie romande, 108, p. 115.
- Eberhard, A.A., 1990. Fuelwood calorific values in South Africa. *Suid-Afrikaanse Bosbouydskrif* 152, 17–22.
- Fairhead, J., Leach, M., 1998. Reframing deforestation. Global analyses and local realities: studies in West Africa. Routledge, London pp. xxv + 238. ISBN 0-415-18591-2.
- Fletcher, M.S., Hamilton, R., Dressler, W., Palmer, L., 2021. Indigenous knowledge and the shackles of wilderness. *Proc. Natl. Acad. Sci.* 118 (40), e202218118.
- Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A., Levis, C., Lapola, D.M., Esquivel-Muelbert, A., Jakovac, C., Nobre, C.A., 2024. Critical transitions in the Amazon forest system. *Nature* 626 (7999), 555–564.
- Freyssinet, P., Roquin, C., Muller, J.C., Paquest, H., Tardy, Y., 1990. Geochemistry and mineralogy of soils covering laterites and their use for gold exploration. In: Noack, Y., Nahon, D. (Eds.), *Geochemistry of the Earth's surface and of mineral formation*, 2nd International Symposium, Aix en Provence, France. Chem. Geol., 84, pp. 58–60.
- Giresse, P., Maley, J., Brenac, P., 1994. Late Quaternary palaeoenvironments in the Lake Barombi Mbo (West Cameroon) deduced from pollen and carbon isotopes of organic matter. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 107, 65–78.
- Giresse, P., Maley, J., Doumenge, C., Philipon, N., Mahé, G., Chepstow-Lusty, A., Aleman, J., Lokonda, M., Elenga, H., 2018. Paleoclimatic changes are the most probable causes of the rain forest crisis 2,600 y ago in Central Africa. *Proc. Natl. Acad. Sci. USA* 115 (29), E6672–E6673. Letter. www.pnas.org/cgi/doi/10.1073/pnas.1807615115.
- Giresse, P., Maley, J., Chepstow-Lusty, A., 2020. Understanding the 2500 yr BP rainforest crisis in West and Central Africa in the framework of the Late Holocene: pluridisciplinary analysis and multi-archive reconstruction. *Glob. Planet. Chang.* 192, 1–19. <https://doi.org/10.1016/j.gloplacha.2020.103257>.
- Giresse, P., Maley, J., Chepstow-Lusty, A., 2023. A focus on the last 1000 years of natural environmental changes in the tropical rain forests of West and Central Africa. Can we detect anthropogenic disturbances? *Glob. Planet. Chang.* 220.
- Gobet, E., Tinner, W., Hochuli, P.A., van Leeuwen, J.F.N., Ammann, B., 2003. Middle to late Holocene vegetation history of the upper Engadine (Swiss Alps): the role of man and fire. *Veg. Hist. Archaeobotany* 12, 143–163. <https://doi.org/10.1007/s00334-003-0017-4>.
- Gosselain, O.P., 2002. Poteries du Cameroun Méridional. Styles techniques et rapports à l'identité. CNRS Editions, Paris.
- Gowlett, J.A.J., 2016. The discovery of fire by humans: A long and convoluted process. *Phil. Trans. Royal Soc. B* 371, 20150164.
- Gowlett, J.A.J., Wrangham, R.W., 2013. Earliest fire in Africa: the convergence of archaeological evidence and the cooking hypothesis. *Azania: Archaeol. Res. Africa* 48, 5–30.
- Haldon, J., 2018. History meets palaeoscience: consilience and collaboration in studying past societal responses to environmental change. *Proc. Natl. Acad. Sci. USA* 115 (13), 3210–3218. <https://doi.org/10.1073/pnas.1716912111>.
- Hart, T.B., Hart, J.A., Dechamps, R., Fournier, M., Ataholo, M., 1996. Changes in forest composition over the last 4,000 years in the Ituri basin, Zaire. In: Van der Maesen, L. J.G., Van der Burgt, X.M., Medenbach, Van, de Rooy, J.M. (Eds.), *The biodiversity of African plants*. Kluwer, Dordrecht.
- Hart, T.B., 2001. Forest dynamics in the Ituri Basin (DR Congo). In: Weber, W., White, L. J.T., Vedder, A., Naughton-Treves, L. (Eds.), *African Rain Forest Ecology and Conservation: An Interdisciplinary Perspective*. Yale University Press, New Haven and London, pp. 154–164.
- Hawthorne, D., Mustaphi, C.J.C., Aleman, J.C., Blarquez, O., Colombarelli, D., Daniau, A. L., Marlon, J.R., Power, M., Vannière, B., Han, Y., Hanson, S., 2018. Global Modern Charcoal Dataset (GMCD): a tool for exploring proxy-fire linkages and spatial patterns of biomass burning. *Quat. Int.* 488, 3–17. <https://doi.org/10.1016/j.quaint.2017.03.046>.
- Hawthorne, D., Lawson, I.T., Dargie, G.C., Bocko, Y.E., Ifo, S.A., Garcin, Y., Schefuß, E., Hiles, W., Jovani-Sancho, A.J., Tyrrell, G., Biddulph, G.E., Boom, A., Chase, B.M., Gulliver, P., Page, S.E., Roucoux, K.H., Sjögersten, S., Young, D.M., Lewis, S.L., 2023. Genesis and development of an interfluvial peatland in the central Congo Basin since the Late Pleistocene. *Quat. Sci. Rev.* 305, 107992. <https://doi.org/10.1016/j.quascirev.2023.107992>.
- Hennebelle, A., Aleman, J.C., Ali, A.A., Bergeron, Y., Carcaillet, C., Grondin, P., Landry, J., Blarquez, O., 2020. The reconstruction of burned area and fire severity using charcoal from boreal lake sediments. *The Holocene* 30, 1400–1409. <https://doi.org/10.1177/0959683620932979>.
- Henry, A., Thiéry-Parizot, I., . Des techniques aux territoires nouveaux, regards sur les cultures mésolithiques. Actes de la table-ronde, 22–23 novembre 2012, Maison de la recherche, Toulouse (France). <http://www.palethnologie.org>, pp. 65–83.
- Hoffmann, W.A., Geiger, E.L., Gotsch, S.G., Rossatto, D.R., Silva, L.C.R., Lau, O.L., Haridasan, M., Franco, A.C., 2012. Ecological thresholds at the savanna-forest boundary: how plant traits, resources and fire govern the distribution of tropical biomes. *Ecol. Lett.* 15, 759–768.
- Hubau, W., Van den Bulcke, J., Kitin, P., et al., 2013. Ancient charcoal as a natural archive for palaeofire regime and vegetation change in the Mayumbe, Democratic Republic of Congo. *Quat. Res.* 80, 326–340.
- Hubau, W., Van den Bulcke, J., Bostoen, K., Klist, B.O., Livingstone Smith, A., Defoirdt, N., Mees, F., Nsenga, L., Van Acker, J., Beekman, H., 2014. Archaeological charcoals as archives for firewood preferences and vegetation composition during the late Holocene in the southern Mayumbe, Democratic Republic of the Congo (DRC). *Veget. Hist. Archaeobot.* 23, 591–606. <https://doi.org/10.1007/s00334-013-0415-1>.
- Hubau, W., Van den Bulk, J., Van Acker, J., Beekmann, H., 2015. Charcoal-inferred Holocene fire and vegetation history linked to drought periods in the Democratic Republic of Congo. *Glob. Chang. Biol.* 21, 2296–2308. <https://doi.org/10.1111/gcb.12844>.
- Huntingford, C., Zelazowski, P., Galbraith, D., Mercado, L.M., Sitch, S., Fisher, R., Lomas, M., Walker, A.P., Jones, C.D., Booth, B.B., Malhi, Y., 2013. Simulated resilience of tropical rainforests to CO₂-induced climate change. *Nat. Geosci.* 6 (4), 268–273.
- Ivory, S., Russell, J.M., 2016. Climate and disturbance controls on tropical African forest for the last 60ka. *Quat. Sci. Rev.* 3. <https://doi.org/10.1016/j.qsa.2021.100023>.
- Johnson, D.I., 1993. Dynamic denudation, evolution of tropical, subtropical and temperate landscapes with three tiered soils: toward a general theory of landscape evolution. *Quat. Int.* 7, 67–78.
- Kaal, J., Carrion Marco, Y., Asouti, E., Martín Seijo, M., Martínez Cortizas, A., Costa Casais, M., Criado Boado, F., 2011. Long-term deforestation in NW Spain: linking the Holocene fire history to vegetation change and human activities. *Quat. Sci. Rev.* 30, 161–175. <https://doi.org/10.1016/j.quascirev.2010.10.006>.
- Kelley, D.I., Burton, Ch., Di Giuseppe, F., et al., 2025. State of Wildfires 2024–2025. *Earth Syst. Sci. Data* 17, 5377. <https://doi.org/10.5194/essd-17-5377-2025>.
- Kiahtipes, C.A., 2016. Late Holocene palaeoenvironments and anthropogenic impacts in the Ngotto Forest, Central African Republic. PhD Dissertation, Southern Methodist University.
- Kiahtipes, C.A., 2019. Anthropogenic impacts in Africa's rain forests: State of the art. In: Eichhorn, B., Höhn, A. (Eds.), *Trees, grasses and crops. People and plants in sub-Saharan Africa and beyond*, Frankfurter Archäologische Schriften, pp. 257–270.
- Kiahtipes, C.A., Lupo, K., Schmitt, D.N., Ndanga, J.P., Jones, J.G., Lee, R., 2011. Prehistory and the present. Palaeoenvironments in the northern Congo. Before Farming: the archaeology and anthropology of hunter-gatherers, 2, pp. 1–14.
- Lanfranchi, R., 1990. Les industries préhistoriques en RP du Congo et leur contexte paléogéographique. In: Lanfranchi, R., Schwartz, D. (Eds.), *Paysages quaternaires de l'Afrique centrale atlantique*, 406.
- Lanfranchi, R., Schwartz, D. (Eds.), 1990. *Paysages quaternaires de l'Afrique centrale atlantique*. Coll. Didactiques. ORSTOM, Paris, 535 pp.
- Lebamba, J., Vincens, A., Lézine, A.M., Marchant, R., Buchet, G., 2016. Forest-savannah dynamics on the Adamawa plateau (Central Cameroon) during the "African Humid Period termination": a new high-resolution pollen record from Lake Tizong. *Rev. Palaeobot. Palynol.* 235, 129–139.
- Levis, C., Flores, B.M., Moreira, P.A., Luiz, B.G., Alves, R.P., Franco-Moraes, J., Lins, J., Konings, E., Peña-Claros, M., Bongers, F., Costa, F.R., 2018. How people domesticated Amazonian forests. *Front. Ecol. Evol.* 5, 171.
- Lézine, A.-M., Assi-Kaudjhis, C., Roche, E., Vincens, A., Achoundong, G., 2013. Towards an understanding of West African montane forest response to climate change. *J. Biogeogr.* 40 (1), 183–196.
- Locko, M., 1991. Un campement préhistorique à Bissobinam Nord-Est de Libreville (Gabon). *Bull. Soc. Préhist. Fr.* 156–160.
- Lupo, K.D., Schmitt, D.N., Kiahtipes, C.A., Ndanga, J.-P., Young, C.D., Simiti, B., 2015. On intensive late Holocene iron mining and production in the northern Congo Basin and the environmental consequences associated with metallurgy in central Africa. *PLoS One* 10 (7), 1–23.
- Maezumi, S.Y., Elliott, S., Robinson, M., Betancourt, C.J., Gregorio de Souza, J., Alves, D., Grosvenor, M., Hilbert, L., Urrego, D.H., Gosling, W.D., Iriarte, J., 2022. Legacies of Indigenous land use and cultural burning in the Bolivian Amazon rainforest ecotone. *Philos. Trans. R. Soc. B* 377 (1849), 20200499.
- Maley, J., Brenac, P., 1998. Vegetation dynamics, palaeoenvironments and climatic changes in the forests of West Cameroon during the last 28,000 years BP. *Rev. Palaeobot. Palynol.* 99, 157–187.
- Maley, J., Doumenge, C., Giresse, P., Mahé, G., Philipon, N., Hubau, W., Lokonda, M., Tshibamba, J., Chepstow-Lusty, A., 2019. Late Holocene forest contraction and fragmentation in Central Africa. *Quat. Res.* 89, 43–59.
- Marchant, R., Richer, S., Boles, O., Capitani, C., Lane, P., et al., 2018. Drivers and trajectories of land cover change in East Africa: human and environmental interactions from 6000 years ago to present. *Earth Sci. Rev.* 178, 322–378.
- Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J., Prentice, I.C., 2008. Climate and human influences on global biomass burning over the past two millennia. *Nat. Geosci.* 1, 697–702. <https://doi.org/10.1038/ngeo313>.
- Martí Lezana, R., 2003. *Arqueología en el cinturón forestal de Guinea Ecuatorial*. Universidad Nacional de Educación a Distancia, Madrid.

- Mbayu, F.M., Tshibamba, M.J., Hubau, W., Mbidjo, T.V., Tambwe, L.E., Mpanda, N.G., Nazangani, M.N., Beeckman, H., Nshimba, H.S., Ngbolua, K.T.N., 2016. Anthracological study and elucidation of the origin of disturbances of the forests of the Yoko reserve forest and its surroundings (Tshopo province, DR Congo). *International J. Innov. Sci. Res.* 26 (1), 205–217.
- McBrearty, S., 1990. Consider the humble termite: Termites as agents of post-depositional disturbance at African archaeological sites. *J. Archaeol. Sci.* 17 (2), 111–143.
- McLauchlan, K.K., Higuera, P.E., Miesel, J., Rogers, B.M., Schweitzer, J., Shuman, J.K., Tepley, A.J., Varner, J.M., Veblen, T.T., Adalsteinsson, S.A., Balch, J.K., 2020. Fire as a fundamental ecological process: research advances and frontiers. *J. Ecol.* 108 (5), 2047–2069. <https://doi.org/10.1111/1365-2745.13403>.
- McMichael, C.H., Correa-Metrio, A., Bush, M.B., 2012. Pre-Columbian fire regimes in lowland tropical rainforests of southeastern Peru. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 342, 73–83.
- Mercader, J., Marti, R., 2003. The Middle Stone Age occupations of Atlantic central Africa: new evidence from Equatorial Guinea and Cameroon. In: Mercader, J. (Ed.), *Under the canopy: the archaeology of tropical rain forests*. Rutgers University Press, New Brunswick, pp. 64–92.
- Mercader, J., Marti, R., Martinez, J.L., Brooks, A., 2002. The nature of ‘stone-lines’ in the African Quaternary record: archaeological resolution at the rainforest site of Mosumu, Equatorial Guinea. *Quat. Int.* 89, 71–79.
- Mesfin, I., Oslisly, R., Forestier, H., 2021. Technological analysis of the quartz industry of Maboue 5 - Layer 3 (Lope National Park, Gabon): implications for the Late Stone Age emergence in western Central Africa. *J. Archaeol. Sci. Reports*, p. 39.
- Moeyersons, J., 1978. The behaviour of stones and stone implements, buried in consolidating and creeping Kalahari Sands. *Earth Surf. Proc.* 3, 115–128. <http://creativecommons.org/licenses/by/4.0/>.
- Moore, H.R., Crocker, A.J., Belcher, C.M., Meckler, A.N., Osborne, C.P., Beerling, D.J., Wilson, P.A., 2022. Hydroclimate variability was the main control on fire activity in northern Africa over the last 50,000 years. *Quat. Sci. Rev.* 288, 107578.
- Moyersson, J., 1987. The concentration of stones into a stone-line, as a result from subsurface movements in fine and loose soils in the tropics. *Geo-Eco-Trop.* II 1-4, 11–22.
- Neumann, K., Bostoen, K., Höhn, A., Kahlheber, S., Ngomanda, A., Tchiengué, B., 2012. First farmers in the Central African rainforest: a view from southern Cameroon. *Quat. Int.* 249 (6), 53–62.
- Ngutsop, F., Servant-Vildary, S., Servant, M., 2004. Late Holocene climatic changes in West Africa, a high-resolution diatom record from equatorial Cameroon. *Quat. Sci. Rev.* 23, 591–609.
- Ngutsop, F., Bentaleb, I., Favier, C., Bietrix, S., Martin, C., Servant-Vildary, S., Servant, M., 2013. A late Holocene palaeoenvironmental record from Lake Tizong, northern Cameroon using diatom and carbon stable isotope analyses. *Quat. Sci. Rev.* 72, 49–62.
- Oslisly, R., White, L.J.T., 2007. Human impact and environmental exploitation in Gabon during the Holocene. In: Denham, T., Iriarte, J., Vrydaghs, L. (Eds.), *Rethinking Agriculture: Archaeological and Ethnoarchaeological Perspectives*. Left Coast Press, California, pp. 345–358.
- Pausas, J.G., Fernandez-Muñoz, S., 2012. Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Clim. Chang.* 110, 215–226. <https://doi.org/10.1007/s10584-011-0060-6>.
- Peyrot, B., Clist, B., Oslisly, R., 1990. Le gisement des “Sablières” de Libreville: étude géomorphologique et archéologique d’un site préhistorique de l’Estuaire du Gabon. *L’Anthropologie* 94 (3), 483–498.
- Peyrot, B., Oslisly, R., Abdessadok, S., Fontugne, M., Hatte, C., White, L., 2003. Les paléoenvironnements de la fin du Pléistocène et de l’Holocène dans la réserve de la Lopé (Gabon): approche par les indicateurs géomorphologiques, sédimentologiques, phytologiques, géochimiques et anthropogènes des milieux enregistreurs de la dépression de la Lopé. *L’Anthropologie* 107, 291–307.
- Pfeifer, M., Shirima, D.D., 2021. Inventory hints at the future of African forests. *Nature* 593 (7857), 42–43.
- Picornell-Gelabert, L., 2020. An archaeological approach to people-tree interactions: The ethnoarchaeology of firewood procurement and consumption among the Benga people of the island of Mandji (Corisco, Equatorial Guinea, Central Africa). *J. Archaeol. Sci. Reports* 34, part A, 102591.
- Picornell-Gelabert, L.L., Asouti, E., Allué Marti, E., 2011. The ethnoarchaeology of firewood management in the Fang villages of Equatorial Guinea, central Africa: Implications for the interpretation of wood fuel remains from archaeological sites. *J. Anthropol. Archaeol.* 30, 375–384.
- Pinçon, B., 1990. La métallurgie du fer sur les plateaux Teke (Congo). Quelles influences sur l’évolution des paysages au cours des deux derniers millénaires. In: Lanfranchi, R., Schwartz, D. (Eds.), *Paysages quaternaires de l’Afrique centrale atlantique*, 479–492.
- Pinçon, B., 1991. Archéologie des plateaux et collines Teke (République Populaire du Congo): de nouvelles données. 8 (9), 24–32.
- Reynaud-Farrera, I., Maley, J., Wirmann, D., 1996. Végétation et climat dans les forêts du sud-ouest Cameroun depuis 4770 ans BP: analyse pollinique des sédiments du lac Ossa. *C. R. Acad. Sci. Paris* 322, 749–755.
- Roberts, P., Hamilton, R., Piperno, D.R., 2021. Tropical forests as key sites of the “Anthropocene”: Past and present perspectives. *Proc. Natl. Acad. Sci.* 118 (40), e2109243118.
- Roquin, C., Freyssinet, P., Novikoff, A., Tardy, Y., 1991. Geochemistry of termitaria and soils covering ferricrete: Application to gold exploration in Africa. In: *EuroLat’91*. Technical University, Berlin.
- Rünge, J., 2001. On the age of stone-lines and hillwash sediments in the eastern Congo basin: palaeoenvironmental implications. *Palaeoecol. Africa* 27, 19–36.
- Salzmann, U., Hoelzmann, P., 2005. The Dahomey Gap: an abrupt climatically induced rain forest fragmentation in West Africa during the late Holocene. *Holocene* 15, 190–199.
- Salzmann, U., Hoelzmann, P., Morczinek, I., 2002. Late Quaternary climate and vegetation of the Sudanian zone of Northeast Nigeria. *Quat. Res.* 58, 73–83.
- Sankaran, M., Hanan, N.P., Scholes, R.J., Ratnam, J., Augustine, D.J., Cade, B.S., Gignoux, J., Higgins, S.L., Le Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K.K., Coughenour, M.B., Diouf, A., Ekaya, W., Feral, C.J., February, E.C., Frost, P.G.H., Hiernaux, P., Hrabar, H., Metzger, K.L., Prins, H.H.T., Ringrose, S., Sea, W., Tews, J., Worden, J., Zambatis, N., 2005. Determinants of woody cover in African savannas. *Nature* 438, 846–849.
- Schefuß, E., Schouten, S., Schneider, R.R., 2005. Climatic controls on central African hydrology during the past 20,000 years. *Nature* 437 (7061), 1003–1006.
- Schoenbrun, D.L., 1998. A green place, a good place: agrarian change, gender, and social identity in the Great Lakes Region to the 15th Century. *Soc. Hist. Africa*, XIV, 302 pp.
- Schwartz, D., 1996. Prehistorical archaeology and formation processes of stone-lines in Central Africa (Congo-Brazzaville and adjoining areas). *Geo-Eco-Trop* 20 (1-4), 15–38.
- Schwartz, D., 2014. Comment on “Geochronological arguments for a close relationship between surficial formation profiles and environmental crisis (c. 3000–2000 BP) in Gabon (Central Africa)” - D. Thiéblemont et al., 2013, C.R. Geosciences 345, 272–283. *C.R. Geosci* 346, 206–208.
- Schwartz, D., Gebhardt, A., 2011. L’enfouissement de vestiges archéologiques par la bioturbation: la colline du Hexenberg (Leutenheim, 67) – un cas d’école. *Etud. Gest. Sols* 18, 287–300.
- Scott, A.C., 2018. *Burning planet: the story of fire through time*. Oxford University Press, Oxford.
- Sheil, D., Bargaño-Tobella, A.U., Ibisch, P.L., Makarieva, A.C., Morris, C.E., Murdiyarso, D., Nobre, A.D., Poveda, G., Spracklen, D.V., Sullivan, C.A., Tuinenburg, O.A., van der Ent, R.J., 2019. Forest restoration: Transformative trees. *Science* 18, 366(6463), 316–317 doi: <https://doi.org/10.1126/science.aay7309>.
- Simpson, A.H., Richardson, S.J., Laughlin, D.C., 2016. Soil-climate interactions explain variation in foliar, stem, root and reproductive traits across temperate forests. *Glob. Ecol. Biogeogr.* 25 (8), 964–978. <https://doi.org/10.1111/geb.12457>.
- Soula, S., Kigotsi Kasereka, J., Georgis, J.F., Barthe, C., 2016. Lightning climatology in the Congo Basin. *Atmos. Res.* 178, 304–319.
- Stager, J.C., Anfang-Sutter, R., 1999. Preliminary evidence of environmental changes at Lake Bambili (Cameroon, West Africa) since 24,000 B.P. *J. Paleolimnol.* 22, 319–330.
- Staver, A.C., Archibald, S., Levin, S.A., 2011. The global extent and determinants of savanna and forest as alternative biome state. *Science* 334, 230. <https://doi.org/10.1126/science.1210465>.
- Stoops, G., 2003. Guidelines for the analysis and description of soil and regolith thin sections. *SSSA, Madison*, p. 184.
- Sullivan, A., Bird, D., Perry, G., 2017. Human behaviour as a long-term ecological driver of non-human evolution. *Nat Ecol. Evol.* 1, 0065.
- Sweeney, L., Harrison, S.P., Vander Linden, M., 2022. Assessing anthropogenic influence on fire history during the Holocene in the Iberian Peninsula. *Quat. Sci. Rev.* 287, 107562.
- Taylor, N., 2016. Across woodlands and rainforests: a systematic re-appraisal of the Lupemban Middle Stone Age. In: Jones, S., Stewart, B. (Eds.), *Africa from MIS 6.2: Population Dynamics and Palaeoenvironments*. Springer, Dordrecht, pp. 273–299.
- Temoltzin-Loranza, Y., Gobet, B., Vannière, B., van Leeuwen, J.F.N., Wienhues, G., Szidat, S., Courtney-Mustaphi, C., Kishe, M., Muschick, M., Ole Seehausen, O., Grosjean, M., Tinner, W., 2023. A chronologically reliable record of 17,000 years of biomass burning in the Lake Victoria area. *Quat. Sci. Rev.* 301, 107915. <https://doi.org/10.1016/j.quascirev.2022.107915>.
- Thiéblemont, D., 2013. Evidence for an aeolian origin of the Holocene lateritic surface cover of Gabon (Central Africa). *Quat. Int.* 296, 176–197.
- Tovar, C., Breman, E., Brncic, T., Harris, D.J., Bailey, R., Willis, K.J., 2014. Influence of 1100 years of burning on the central African rainforest. *Ecography* 37, 001–010. <https://doi.org/10.1111/ecog.00697>.
- Tshibamba Mukendi, J., Hubau, W., Morin-Rivat, J., Ntahobavuka, H., 2014. Charcoal records reveal past occurrences of perturbations in the forests of the Kisangani region (RDC): vegetation history of the semi-deciduous rainforest. EuropeanGeosciences Union (EGU) General Assembly of the Kisangani region, Vienna, Austria [AT]. Poster presentation.
- Tutin, C.E.G., White, L.J.T., Mackangamissandzou, A., 1996. Lightning strike burns large forest tree in the Lopé Reserve, Gabon. *Global Ecol. Biogeogr. Lett.* 5, 36–41.
- Vachula, R.S., Rehn, E., 2022. Modeled dispersal patterns for wood and grass charcoal are different: Implications for paleofire reconstruction. *The Holocene* 33 (2), 159–166.
- Vachula, R.S., Richter, N., 2018. Informing sedimentary charcoal-based fire reconstructions with a kinematic transport model. *Holocene* 28, 173–178.
- Vachula, R.S., Russell, J.M., Huang, Y., Richter, N., 2018. Assessing the spatial fidelity of sedimentary charcoal size fractions as fire history proxies with a high-resolution sediment record and historical data. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 508, 166–175.
- Vannière, B., Blarquez, O., Rius, D., Doyen, E., Brücher, T., Colombaroli, D., Connor, S., Feurdean, A., Hickler, T., Kaltenrieder, P., Lemmen, C., Leys, B., Massa, C., Olofsson, J., 2016. 7000-year human legacy of elevation-dependent European fire regimes. *Quat. Sci. Rev.* 132, 206–212. doi: 10.1016/j.qua.sci.rev.2015.11.012.
- Vincent, P.L., 1966a. Les formations meubles superficielles au Sud du Congo et du Gabon. Mission 1964–1965. Rapport BRGM 65 BRA 009.
- Vincent, P.L., 1966b. Les formations meubles superficielles au Sud du Congo et du Gabon. Mission 1964–1965. Bulletin du BRGM 4, 53–111.

- Vleminckx, J., Morin-Rivat, J., Biwolé, A.B., Daïnou, K., Gillet, J.-F., Doucet, J.-L., Drouet, T., Hardy, O., 2014. Soil charcoal to assess the impacts of past human disturbances on tropical forests. *PLoS One* 9 (11), e108121. <https://doi.org/10.1371/journal.pone.0108121>.
- White, F., 1983. The vegetation of Africa: a descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa Natural Resources Research, XX. UNESCO, Paris.
- Willis, K.J., Bennett, K.D., Burrough, S.L., Macias-Fauria, M., Tovar, C., 2013. Determining the response of African biota to climate change: using the past to model the future. *Philos. Trans. R. Soc. B* 368, 20120491.
- Wright, D.K., 2017. Humans as agents in the termination of the African Humid Period. *Front. Earth Sci.* 5, 4. <https://doi.org/10.3389/feart.2017.000>.
- Yao, Y., Ciaï, P., Joetzjer, E., Li, W., Zhu, L., Wang, Y., Frankenberg, C., Viovy, N., 2024. The impacts of elevated CO₂ on forest growth, mortality, and recovery in the Amazon rainforest. *Earth Syst. Dynam.* 15, 763–778.
- Zheng, Z., Ma, T., Roberts, P., Li, Z., Yue, Y., Peng, H., Huang, K., Han, Z., Wan, Q., Zhang, Y., Zhang, X., 2021. Anthropogenic impacts on Late Holocene land-cover change and floristic biodiversity loss in tropical southeastern Asia. *Proc. Natl. Acad. Sci.* 118 (40), e2022210118.