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Past fire dynamics in sub-Saharan Africa during the last 25,000 years: Climate change and increasing human impacts

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ABSTRACT

The aim of this study is to provide the drivers of long-term fire dynamics in various regions of Sub-Saharan Africa using a synthesis of updated sedimentary charcoal records, from 25,000 years ago to the present. We used the charcoal data currently available in the Global Paleofire Database, updated with the most recent published charcoal data, to reconstruct past biomass burning across the continent. We analyzed standardized charcoal data grouped by region (central Africa, eastern Africa, southern Africa, and Indian Ocean) and by vegetation type (forest, savanna, and shrubland). Within this framework, we found that quality data were lacking to reconstruct a robust trend in biomass burning before 5000 years at the continental scale. This large spatial scale was indeed masking regional peculiarities. Our results suggest that past changes in biomass burning were nuanced and cannot be simply attributed to either climate- or humans, and that they varied from each sub-regions and vegetation type history. In central Africa, biomass burning increased after the end of the African Humid Period and the first wave of Bantu-speaking people migration, whereas in East Africa and the Indian Ocean islands, it seems that human population growth was the main driver of fire activity. In South Africa, reduced rainfall seemed to offset fire activity due to population growth by reducing potentially flammable biomass. While the diversity of methodological techniques used to produce charcoal quantification made comparisons difficult, regional patterns still emerged from these data. This synthesis thus highlights the need to increase the number of sites with charcoal

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data and to harmonize charcoal extraction and quantification methods across Africa to improve regional to continental assessments of fire histories.

1. Introduction

With more than 70% of the area burned worldwide each year, Africa is called “the fire continent” (Giglio et al., 2013). Except in deserts, fire plays a critical role in shaping “African” landscapes (e.g. Bond, 2005; Lehmann et al., 2014). Indeed, fire, whether natural or anthropogenic, alongside herbivory, regional climate and local edaphic factors, modulates ecosystems structure, composition and distribution (Scholes and Archer, 1997; Bond and Keeley, 2005; Staver et al., 2011; Bond, 2019; Aleman et al., 2020). While tropical forests rarely burn (Cochrane and Schulze, 1999), some climatic conditions, especially intense and repeated droughts, sometimes associated with human impact, allow fire to propagate into forest (Hennenberg et al., 2008; Ibanez et al., 2013) with consequences on tree mortality (Balch et al., 2011) and forest composition. Evidence of past fires in African tropical forests has thus been recorded (Hubau et al., 2015). Among the tropical grassy biomes in Africa, dominated by a C₄ grassy understory, savanna and grassland evolution and maintenance depend on frequent fires at interannual to decadal scales (Scott, 2000; Lehmann et al., 2014; Hempson et al., 2018). Fire has thus been a dominant force of disturbance on the continent for millions of years (Scott, 2000), and the current distribution of forest and grassy biomes is thought to be inherited from past fire-climate interactions, especially during the Holocene when human influence increased (Vleminckx et al., 2014; Cole et al., 2014; Morin-Rivat et al., 2017; Aleman et al., 2019).

Climate, especially rainfall and its seasonality (Archibald et al. 2010; Archibald et al., 2013), is often considered as the main broad-scale driver controlling the different components of fire regimes today and in the past, in particular the probability and timing of ignitions, and the dryness of the vegetation (Beerling and Osborne, 2006). However, the ecological success and spread of anatomically modern humans and their ancestors created additional ignition sources (Archibald et al., 2012; Berna et al., 2012) and the shift in the fire seasons has changed fire intensity and burned surface area which increased fire impact on landscapes for at least the past million years (Archibald et al., 2012; Glikson, 2013; Archibald, 2016). Reconstructions of long-term fire patterns are therefore critical to assess how past climate influenced fire regimes as the human factor increasingly became a key global driver of fire regimes.

Charcoal particles accumulated in sediments provide a method for reconstructing past biomass burning and fire activity (e.g. Scott and Glasspool, 2006; Hawthorne et al., 2018). Still, challenges remain in interpreting tropical grassy ecosystem records because very few studies have examined the link between charcoal accumulation and fire regime parameters such as fire frequency, burned area or fuel type (Duffin et al., 2008; Aleman et al., 2013; Maezumi et al., 2021). Indeed, compared to boreal or temperate forests that burned less frequently and for which fire events are identified using charcoal accumulation peaks (Higuera et al., 2007; Brossier et al., 2014), it is challenging to reconstruct the fire return interval (FRI) in grassy ecosystems because sites with high-enough sedimentation rates to isolate these high-frequency fire events (between 1 and 10 years according to Archibald et al. (2013)) are rare.

Nevertheless, the amount of charcoal particles recorded in sediments can be used as a proxy for biomass burning and fire activity (Marlon et al., 2008). For forests for which trees are the main fuel type this can provide information about the severity of fires (e.g. Tovar et al., 2014; Maezumi et al., 2021) – i.e. its impact on aboveground vegetation related to mortality – but for grassy ecosystems, it can be related to the frequency of fires or the area burned (Duffin et al., 2008), and even to the flammability of the vegetation in a landscape (Pausas et al., 2017). Interpreting charcoal records in terms of fire parameters in tropical en-

vironments is therefore complicated and is still being developed (Hawthorne et al., 2018). Moreover, there are large variations in charcoal fragment size classification and extraction methods (e.g. sieving vs pollen slides) used in charcoal analysis across studies (Vachula, 2019), with large (> 150 µm) and small (< 50 µm) charcoal fragments potentially recording fires from different spatial scales (Vachula et al., 2018). The lack of standardized methodology, nomenclature and defined units for charcoal analysis makes absolute comparison of charcoal records across sites challenging (Hawthorne et al., 2018; McMichael et al., 2021).

Charcoal records can still be combined, even with different units, using spatiotemporal composites through a process of rescaling transformation and standardization (Marlon et al., 2008; Power et al., 2010; Blarquez et al., 2014). Composites show general trends of biomass burning over long-time scales and over large areas, from local to continental and even global scales (e.g. Marlon et al., 2008). Despite being known as the fire continent, the paucity of sedimentary charcoal records in Africa limits assessments of past biomass burning trends at regional and continental scales (Marlon et al., 2016).

Here we make an inventory of the data currently available, and their quality (chronological controls and quantification method), in the Global Paleofire Database (GPD, <https://paleofire.org/>), updated with the most recent published data. The Global Paleofire Database, formerly known as the Global Charcoal Database, was established about fifteen years ago (Marlon et al., 2008) and has proven to be a very powerful tool for obtaining a large-scale view of the temporal dynamics of fires and as a repository for paleofire records. Charcoal records from the GPD have been used for generating spatiotemporal composites of fire activity in Africa and elsewhere (Marlon et al., 2016; Adeye et al., 2022), but the quality and potentially different signals for the African regions needed to be better explored. We then discuss the trends in biomass burning at the continental scale, and for sub-regions and ecosystems, which is crucial for Africa given the peculiar history in past climate changes, human societal evolution in different regions and the different flammability of ecosystems (Dabengwa et al., 2021). Ecosystems were thus grouped into three types reflecting ecological functioning, vegetation flammability and fire regimes: tropical forests, savannas and shrublands (White, 1983; Adeye et al., 2022). Trends in biomass burning were studied at the sub-regions scale because the timing of past climate changes as well as patterns of human use of fire are expected to differ (Tovar et al., 2014; Mustaphi et al., 2022; Mosher et al., 2024). While herbivores can have a strong impacts on ecosystems structure and composition, and even on fire regime by reducing available fuel, even more so in the past (Hempson et al., 2015), this disturbance, which is intertwined with the others, has been little studied (Bond and Keeley, 2005) and is currently impossible to quantify in the past at the scale of the current study. We therefore cross-examine the charcoal records with proxies of past climate and population densities with the aim of assessing the long-term drivers of fire dynamics in Africa. In so doing, we investigate the patterns, issues and gaps that emerge regionally in relation to past climate and human land-use changes.

2. Materials and methods

2.1. Charcoal data available for Africa

The charcoal dataset used in this study was extracted from the Global Paleofire Database (GPD, accessed January 15, 2024) and complemented with charcoal data recently published (Mustaphi et al. 2021, 2022; Reinhardt et al., 2022; Dabengwa et al., 2022; Razanatsoa et al., 2022; Montade et al., 2023), and which correspond to sedimentary

charcoal records from terrestrial cores (Fig. 1). Northern African records were excluded because the regional climate and human occupation history are significantly different from the rest of the continent (Keeley et al., 2011; Vicente and Schlebusch, 2020). Terrestrial soil profiles and soil profiles were excluded because they do not present useable temporal stratigraphy. Marine records were excluded because the charcoal particles in marine sediments are assumed to originate from large spatial areas and, consequently, are potentially sourced from multiple vegetation types (Genet et al., 2021).

Among the 115 sites available in the database, 67 were selected for data criteria and accessibility, their age model, and their localization in Africa (Fig. 1). Indeed, only sites with at least three chronological determinations available to establish the best age-depth model and with charcoal measurement data (quantity, number, time step, continuity) were kept (SI Table 1 and SI Fig. 2 Raw data). We have indicated and located the number of sites with pollen fossil records available in the African Pollen Database (<https://africanpollendatabase.ipsl.fr/#/home>), allowing vegetation dynamics to be reconstructed on a continental scale and comparison with charcoal data (Fig. 1, Panel A).

Sedimentary deposit contexts and charcoal counting methods remain heterogeneous, corresponding to a dozen different methods, mostly “fragments of charcoals sieved at 125 μm or 160 μm per cm^3 or gram”; “charcoal particles on pollen slides, in concentration, in percent or ratio”. Datasets described as “Presence/absence”, “Oxidation Resistant Elemental Carbon”, “% total organic fraction” were not used.

For the 67 records used, age-depth models were re-computed for 1 record (Lake Albert) and influxes computed based on concentration of macro (sieving method) and micro-charcoals (pollen slide method) for 4 records (Sidi Ali, Doukoulou, Gbali and Nguene), using the pretreatment function (paleofire R package by Blarquez et al. (2014)) in order to resample the records to equal time intervals. We then applied the standardization of the data proposed by Power et al. and Blarquez et al. (2014; 2014) in order to make the influx of charcoal comparable over time and sites. This standardization protocol includes: (1) homogenizing the variance using the Box-Cox transformation, (2) rescaling the values with a minimax transformation, and (3) a final rescaling to Z-scores. Charcoal influx timeseries were then averaged according to the region or the vegetation group (see further) to create composite series with ranges and trends. We used the “paleofire” R package (Blarquez et al., 2014) for charcoal series standardization (Z-Scores) and to build the composite series, which were then considered as trends of past biomass

burning (Marlon et al., 2016), that can be interpreted as “fire severity” (Maezumi et al., 2021) for forests, as it potentially reflects vegetation mortality, but that is probably more related to burned area or the frequency of fires in savanna environment (Duffin et al., 2008). We have chosen to use the data standardization proposed by Marlon et al. (2008) because it has been used many times on all continents and the data generated in this way can be compared. However, we are aware that the methodology is not perfect; other approaches such as that proposed by McMichael et al. (2021) could be used in a future study when new data becomes available.

Four Sub-Saharan regions provide the geographic focus for this study: Central Africa, Eastern Africa, Southern Africa, and Indian Ocean (Fig. 1). Northern and Western Africa are not covered in this analysis, because in Northern Africa the regional climate and human occupation history are significantly different from the rest of the continent (Keeley et al., 2011) and due to the absence of useable paleofire history data in Western Africa.

Within each designated geographic region, each record was assigned to one of three vegetation groups (Fig. 1, panel C; Forest, Shrub and Savanna) in order to reflect different potential flammability and fire-vegetation feedbacks. These vegetation groups were delineated from the vegetation units defined in White’s (1983) vegetation map. The “Forest” group includes “Lowland rain forest (lowland and drier)” and “swamp forest”; the “Savanna” group includes “Forest transitions and mosaics”, “Woodland” and “Woodland mosaics and transitions” (*nb*. The term “mosaics” in White’s classification is associated with the presence of secondary grasslands and a grass cover) and “Grassland”; the “Shrub” type groups “Bushland and Thicket”, “Cape shrubland”, “Transitional scrubland” and “Afromontane vegetation”. The savanna group consists of a spectrum of seasonally dry vegetation types characterized by the presence of grass with varying woody cover, therefore experiencing recurrent low-intensity fires due to the grass cover (Scholes and Archer, 1997; Archibald et al., 2013). This is why we included in this group the “Forest transitions and mosaics”, along with woodland, which correspond to a mosaic of forest and savanna experiencing frequent fire today and in the past (Aleman et al., 2019). The last group, consists of shrublands, located mainly in southern Africa, where fires are frequent and intense (Archibald et al., 2013).

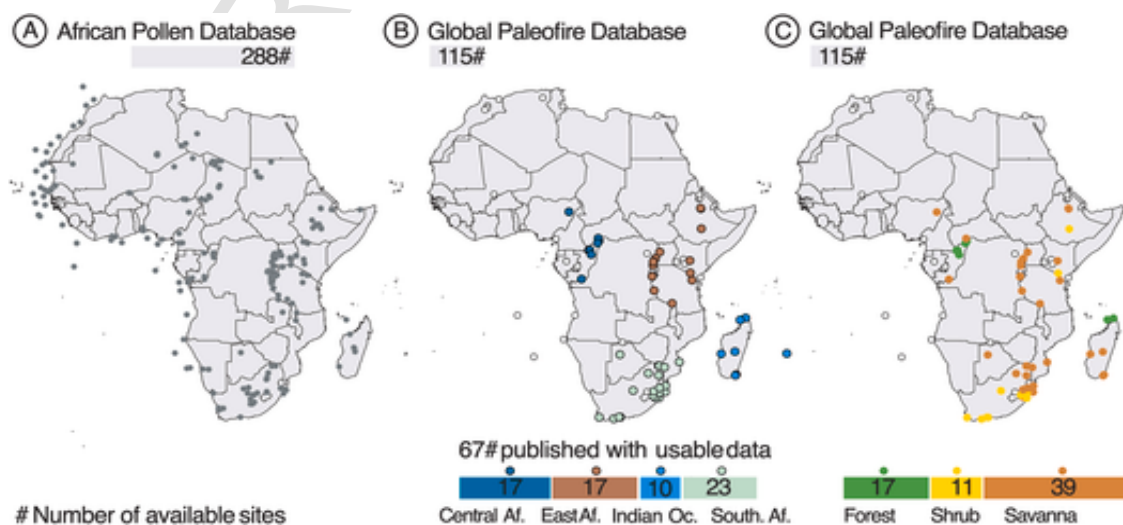


Fig. 1. Comparison between the African Pollen Database (panel A – grey dots) (Lézine et al., 2021) and the Global Paleofire Database GPD (white dots with a border: existing data but not currently available or excluded). Four Sub-Saharan geographic regions were defined according to the distribution of available sites: Central Africa, Eastern Africa, Southern Africa and Indian Ocean (panel B).

2.2. Past human density and climate datasets

In order to discuss the trend of past biomass burning in relation to human population density and past climate in the four Sub-Saharan regions we used the temporal evolution of the number of archaeological sites from regional datasets: Seidensticker et al. (2021) for Central Africa, Mustaphi and Marchant (2016) for East Africa, Douglass et al. (2019) for Indian Ocean (only Madagascar) and Loftus et al. (2019) for Southern Africa. The computed curves are the median and 5th and 95th percentiles of kernel densities with a bandwidth of 60 years of 1000 sets of calibrated dates, each of them drawn from a radiocarbon date according to its probability distribution following calibration with the IntCal20 or SHcal20 calibration curves (Hogg et al., 2020; Reimer et al., 2020) depending on their location.

Good-quality past climate data is very rare in Africa. We have therefore selected the best available datasets for each geographical region. They are not always the same proxy, but they are all supposed to indicate changes in rainfall: the δD_{wax} of Lake Barombi in Cameroon from Garcin et al. (2018) was chosen for Central Africa. The δD_{wax} of Lake Challa at the Tanzania–Kenya border from Tierney et al. (2011) was chosen for Eastern Africa. For the Indian Ocean we used the smooth spline of the z-score-transformed measures of the $\delta^{18}O$ curve from the Rodrigues speleothem from Li et al. (2020). Finally, two rainfall curves for Southern Africa were used according to the Northern and the Central & Eastern precipitation stack estimated by Chevalier and Chase (2015) because of distinct rainfall seasonality gradients.

3. Results and discussion

3.1. Biomass burning at the continental scale

The oldest available records start about 25,000 yr cal. BP (Fig. 2). However, no general pattern for the late Pleistocene (before 15,000 yr cal. BP) can be correctly interpreted due to the scarcity of

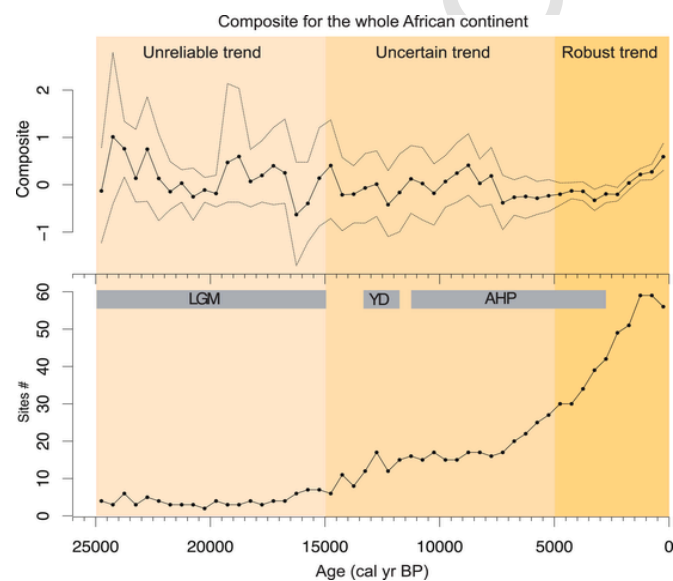


Fig. 2. Trends in biomass burning at the continental scale inferred from charcoal abundance records. The composite charcoal series (A) were computed for the 64 sites available for Africa with a 500-year bin width (associated confidence interval with dashed lines corresponding to the 2.5th and 97.5th percentiles) and the number of sites contributing to composite value at each time step (B). LGM, Last Glacial Maximum; YD, Younger Dryas; AHP, African Humid Period.

comparable data (less than six records are available and only in eastern Africa).

After 15,000 yr cal. BP, the number of paleofire records available increases (10 to more than 25 at 5000 yr cal. BP) but the confidence intervals remain large (Fig. 2). This means that trends are relatively diverse across the continent, which requires caution when interpreting the biomass burning composite at this spatial scale.

No single, simple pattern emerges across the entire continent during this period, despite major changes in climate and vegetation conditions during the Younger Dryas and at the end of the African Humid Period (Shanahan et al., 2015): 25,000 yr BP and 15,000 yr BP and especially during Heinrich Stadium 1, intertropical Africa experienced the driest period since 25,000 yr; then there was, during the Younger Dryas, a very rapid increase in rainfalls which will continue throughout the African Humid Period and decrease again 5000 yr BP. This could be explained by too few data but more probably because fire regimes associated with changes in climate (precipitation) and vegetation have differed markedly across the continent and by vegetation type. This is consistent with recent results showing that fire activity response to increased rainfall were not linear during the African Humid Period (Karp et al., 2023), with increased fire activity for arid and semi-arid vegetation (fuel-load limited) but decreased fire activity for more mesic vegetation (fuel-moisture limited).

A more robust trend in charcoal composite begins around 5000 yr cal. BP, supported by a comparatively large number of records (more than 70% of sites are dated with more than three ^{14}C dates from this time period), showing also an increase in biomass burning (Fig. 2). This trend appears to coincide with changes in human population density and land-use practices at the continental scale linked to the Bantu expansion and Iron Age across the continent at that time (Seidensticker et al., 2021; Saulieu et al., 2021). Because Bantu expansion occurred in different waves and at different times in different regions, it is necessary to downscale the analysis to the regional level, integrating vegetation, landscapes and agro-pastoral dynamics, which will permit more precise interpretations and state stronger hypotheses.

3.2. Regional burning and human demographic fluctuations

The four regions show contrasting trends in biomass burning and human activity history (Fig. 3). In **Central Africa** (Fig. 3a), biomass burning remains relatively constant until 1500 yr cal. BP despite changes in climatic conditions at the end of the AHP (Shanahan et al., 2015). In particular, starting 4000 years ago until 2500 years ago, dry season length has probably increased, leading to changes in vegetation structure and composition (Salzmann and Hoelzmann, 2005; Giresse et al., 2020), and influencing land use patterns (Neumann et al., 2012). During this period, the Bantu-speaking populations migrated from the border of Cameroon and Nigeria to the Congo Basin (Bostoen et al., 2013; Maret, 2013; Seidensticker et al., 2021). As farmers and metallurgists (Neumann et al., 2012; Bostoen et al., 2015; Grollemund et al., 2015), they are thought to have impacted vegetation (Garcin et al., 2018) and increased fire activity (Aleman et al., 2019) through their land-use practices. However, the lack of change in the regional charcoal composite (Fig. 3a) around 2500 yr cal. BP makes it difficult to assess the possible role of human activities on fire regimes at this scale. After, charcoal data show an increase in biomass burning while Bantu populations were collapsing in Central Africa ca. 1500 yr cal. BP (Seidensticker et al., 2021; Saulieu et al., 2021). For the last 1000 years, the burned biomass has continued to increase at the same time as the population has also increased. This complex relationship between fire and human signals may have three possible explanations: (1) early Bantu expansion may not have been immediately associated with significant deforestation through slash-and-burn farming (Bayon et al., 2012; Garcin et al., 2018), while the increase in biomass burning during the second wave of Bantu immigration (ca. 1500 yr cal. BP) may be

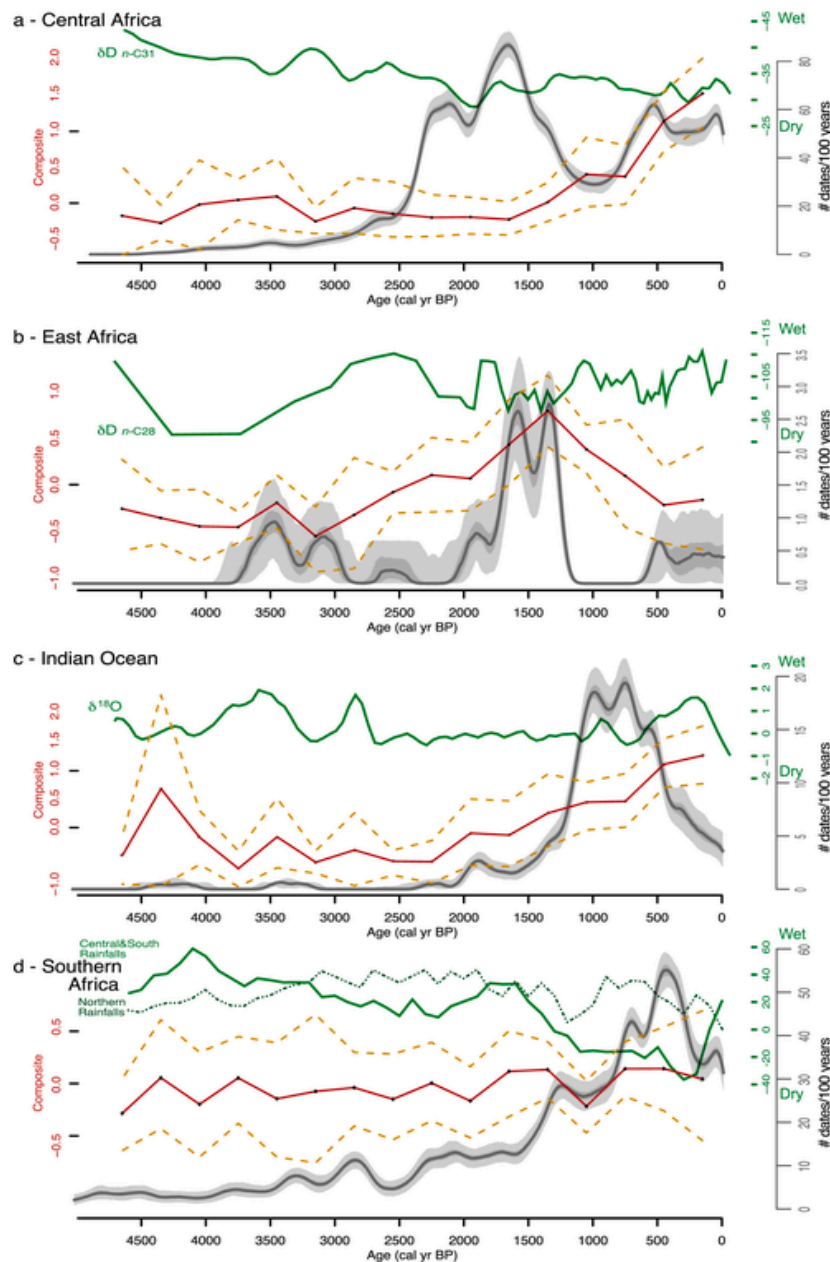


Fig. 3. Trends in biomass burning at the regional level compared to evidence of human activity since 5000 yr cal. BP. Composite charcoal series (red solid lines) and associated 95% confidence interval (yellow dashed lines) were computed for the four regional zones (a–d). An indication of human activity (grey curves) was interpreted using the temporal evolution of the number of archaeological sites from regional datasets. The climate data are represented with the green curves and plotted so that the minima indicate a decrease in rainfall *i. e.* a drier period (see Material and Methods for datasets and computations).

linked to different practices and thus a stronger impact on the fire regime and land cover (Tovar et al., 2014). However, while there were definite changes in cultivation between the Early Iron Age and the Late Iron Age, with very different pottery assemblages (Seidensticker, 2024), the bioarchaeological remains do not show any major changes in cultivated plants (Neumann et al., 2022); (2) The radiocarbon curve only provides a limited perspective on human occupation in this region; (3) The charcoal composite may offer a limited regional picture of biomass burning because of the lack of records proximal to archaeological settlements, or the early Bantu used regular low-intensity fires that existing charcoal records may be insensitive to capturing. Modern calibration studies suggest local and small size-area fires, with limited convection columns, do not disseminate a significant number of charcoal parti-

cles in forested areas except when the recording site is very close to the fires (Aleman et al., 2013).

In East Africa, fire disturbance regimes are important to modifying and maintaining vegetation cover in all of the ecosystems that occur in this region (Colombaroli et al., 2014), from highly frequent burning in grass dominated savannas (intra-annual to decadal scales according to Hempson et al., 2018) to low frequency burning in montane forests (multi-centennial scales (Courtney Mustaphi et al., 2023)). Eastern Africa hydroclimate over the past 5000 years has been characterized by the time transgressive end the AHP and higher spatiotemporal variability since 4000 years (Fig. 3B) with important implications for vegetation and fire of semi-arid regions (Colombaroli et al., 2018; Githubi et al., 2018). This is apparent in the composite curve with an increase in

regional biomass burning around 3000 years and which peaks at approximately 1500 years cal yr BP; this corresponds to the initial phase of the Iron Age in the region and the peak is coincident with the highest number of archaeological radiocarbon dates (Fig. 3). Biomass burning then decreases. Thus, there is a good apparent relationship between the burned biomass curve and the estimated populations even if land use patterns in East Africa are quite complex. Contributions to variations of fire regimes are linked to an overlapping of Middle and Later Stone Age hunter-gatherer-fisher strategies (Shipton et al., 2018), several modes of agriculture or a shift in pastoralist modes over the past 6000 years (Lane, 2004, 2013), intensive agriculture in specific hillslope regions during the Iron Age (eg. Heckmann et al., 2014; Kimaro et al., 2019), and trade networks (Spear, 2000). Modern fire regimes continue to be modified by land uses from grazing pressure, climate change, linear infrastructure, household and community and governmental fire policies (e.g. Probert et al., 2019). Further data generation to fill in geographic and ecological gaps should focus on grassy savannas, small highlands, coastal and high elevation locations. Geographic challenges to data collection are apparent in areas with only ephemeral water and sediment accumulation that limit locations of potential study sites.

Data from **Indian Ocean** mainly come from Madagascar. Unlike the continent, the island was populated by humans relatively recently, with so far, significant human impact reported for the last 2000 years (Douglass et al., 2019). In this region, biomass burning is consistently increasing since the last 2000 years and so does the density of archaeological dating with a more abrupt increase between 1500 and 1000 BP (Fig. 3). While direct relationship between human activity and fire activity has been identified for several study sites in Madagascar (Reinhardt et al., 2022; Broothaerts et al., 2023), the timing and the strength of this relationship seems to be site-dependent. Indeed, in some areas fire activity changes seem to be more linked to climatic changes, especially drought (Virah-Sawmy et al., 2010), with an increase in fires linked to periods of severe drought. Moreover, 1000 years ago, a rainfall decline or a megadrought, may have contributed to increasing the severity (or area) of fires settled by humans, therefore accentuating forest loss (Montade et al., 2023). Only 10 sites are available, which also limits the interpretation knowing that Madagascar's vegetation and climate are highly diverse.

In **Southern Africa** the majority of the available charcoal records are located in the relatively wetter eastern half of the region and on the southwest coast, with very few in the west (Figs. 1 and 3d) this is why we have used the rainfall curve reconstructed by Chevalier and Chase (2015) for the Central and Eastern part of South Africa; however, given that rainfall does not seem to have fallen as much in the north 2000 years ago, we have also plotted the Northern ones' in Fig. 3d. The first Bantu-speaking agricultural communities appear intermittently in the eastern part of the region between 3000 and 2000 years BP, with a substantial increase only after 2000 years BP (Ashley et al., 2016), while Khoe-speaking pastoralists begin arriving in the west and southwest coast only around 2000 years BP (Sadr, 2015). Despite the increasing demographic pressure and land use change in the past two millennia, the regional charcoal does not show a substantial increase (Fig. 3d). Noticeably, most records show that the first spread of farmers and pastoralists occurs at the end of a period of relatively high rainfall, which declines around 1500 years BP. Therefore, the drying conditions may have been responsible for declining biomass and flammability of vegetation and low carrying capacity for high population density. It is only after c. 1000 and 1500 that charcoal curves parallel demographic increase. However, timing and severity of fire varies across the region. The arrival of pastoralists seems to have had relatively little or no substantial impact on fires in the Mediterranean shrublands (Fynbos) of the southwest coast (ex. Cordova et al., 2019), while they had a marked impact on the Kalahari dry savanna of northern Botswana (Cordova et al., 2017), and the grasslands and savannas of the eastern part (Scott, 2002). The eastern half of the region seems to have had a relatively

early strong impact of fire in the more-wooded lowlands, and more paused and a delayed impact on the grasslands on mountains and highlands (Finch et al., 2022), which is consistent with the archaeological age modeling of Bantu-speaking spread in the region (Ashley et al., 2016). Davies et al. (2022) showed that fire activity in South Africa differed greatly between east and west over the last 10,000 years. The signal was highly decorrelated with climate and population growth over the last 2000 years. In the east, there was an increase in fire activity as the climate became dryer and the population increased, while in the west the opposite was true as shown by Mosher et al. (2024). It therefore appears that when analyzed at the scale of South Africa as a whole, the opposing trends produce an average signal that does not necessarily represent the true local trends. These conflicting results highlight the limitations of reconstructing at too large a scale.

3.3. Burning biomass and vegetation structure

Trends in biomass burning since c. 5000 yr cal. BP are strikingly different between the three vegetation groups considered here (Fig. 4), which highlights the importance of the clustering choice for analysis (Vanni re et al., 2016; Connor et al., 2019). Although regional grouping can be influenced by ecosystem diversity and land use differences, vegetation-based clustering is crucial because it differentiates ecosystems by their response to fires and helps us understand how they function with respect to fire (Pausas and Paula, 2012).

In **forests**, biomass burning is the lowest around 5000 yr cal. BP, then slightly increased to stabilize until 1500 yr cal. BP when it increases drastically at unprecedented rates (Fig. 4a). While tropical forests, especially rainforests, rarely burn naturally (Bowman et al., 2016), they can do so when people are present (Bush et al., 2015), though fires rarely spread over large areas. Most of the forest fire history sites are located in the Congo Basin, and fire episodes remained rare despite increasing human population before 1500 yr cal. BP (Fig. 4). So, what did trigger this abrupt change at 1500 yr cal. BP? While precipitation patterns were returning to more humid conditions not reached since the end of the AHP (Vincens et al., 1999; Bremond et al., 2021), localized droughts were recorded throughout the region (Elena et al., 1996; Vincens et al., 1998). Also, increasing anthropogenic pressure through land-use change may have triggered a loss of forest vegetation resilience to climatic stress through disruption of moisture recycling feedbacks, allowing fires to be set and spread over larger areas than previously (Kukla et al., 2021). For example, these fires could explain the large legacy patches of Marantaceae giant herbs in some forests, still visible today (Tovar et al., 2014). In the focus example, Tovar et al. (2014) show that burning started in the last 1100 years, but fire was discontinuous in time and space and asynchronously linked to local human ignitions.

In **savannas**, after some fluctuations, biomass burning has increased steadily since 2500–2000 yr cal. BP (Fig. 4b). The trends throughout inter-tropical Africa are probably more tightly linked to Bantu expansion than to climate changes themselves, especially because the major climate changes that affected all Central Africa occurred earlier, between 3000 and 2500 (Giresse et al., 2020). However, human impact on fire activity has probably been modulated by regional rainfall. Indeed, overall rainfall tended to decrease over this period, but the savannas responded in a contrasting way. While fire activity decreased in arid savannas (mean annual rainfall (MAR) < 800 mm/yr), it increased in mesic ones (MAR between 800 and 1500 mm/yr; see Fig. S1 in Supporting Information), as it was the case at the end of the AHP (Karp et al., 2023). However, the decrease in rainfall observed at this time is not enough to explain the strong increase in fire activity. In the focus example (Fig. 4b "Savanna"), Aleman et al. (2019) interpreted the sharp increase in fire activity 1500 years ago as an intensification of human impact in the region, associated with a loss of resilience in the existing vegetation as it failed to recover with fires probably occurring too

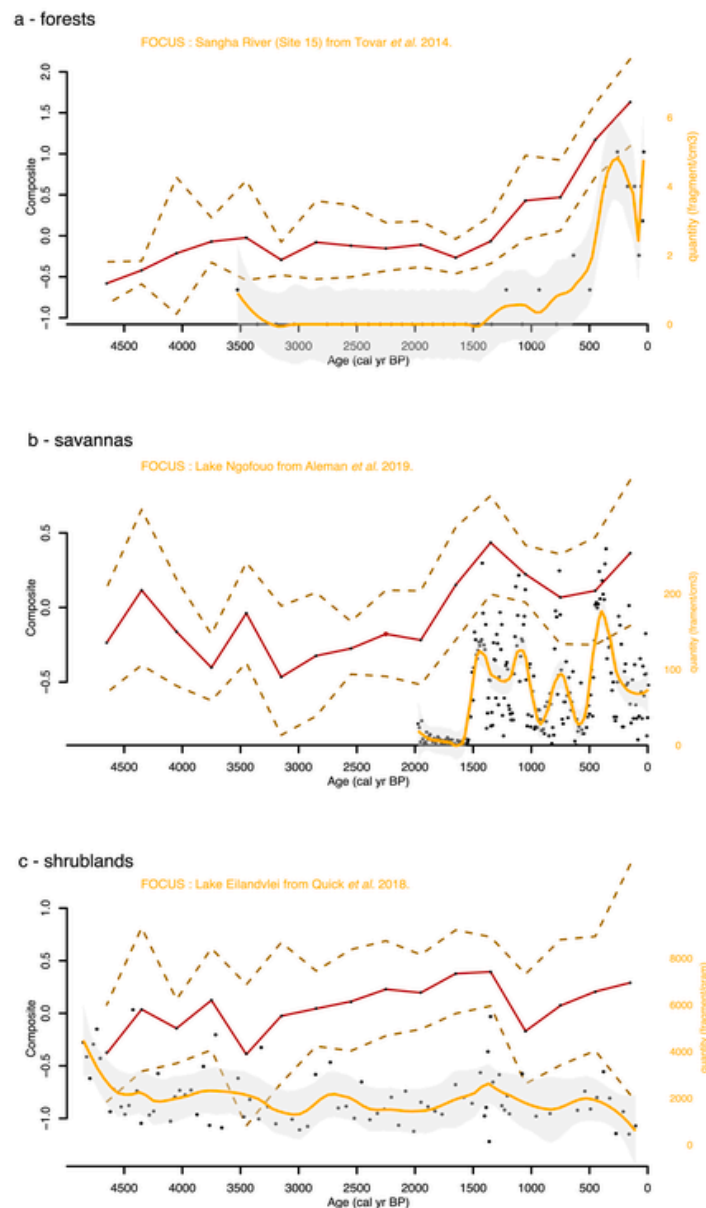


Fig. 4. Trends in biomass burning for the three vegetation groups considered in this study. Composite charcoal series (red solid lines) and associated 95% confidence intervals (dashed lines) were computed for the past 5000 years. Three focus examples for each vegetation type are shown (yellow lines) using the original data from Tovar et al. (2014) for (a) **forests**, Aleman et al. (2019) for (b) **savannas** and Quick et al. (2018) for (c) **shrublands**.

frequently. The recent decrease in charcoal influx recorded at this site, which contrasts with the composite records, may be due to local human use of fire with conversion to croplands and plantations (Archibald et al., 2012; Colombaroli et al., 2014).

In **shrublands**, represented only by South and East African sites, the rise in biomass burning is less evident, and corresponds to a slight increase over the last 5000 years. In Southern Africa, increased human activities were concomitant with a decrease in rainfall (Fig. 3d), and the decrease in biomass burning observed between 1500 and 500 BP was likely associated with a less biomass flammability rather than decreased fire frequency (Dabengwa et al., 2021). This could be the consequence of short fire-return intervals leading to an overall loss of biomass from the ecosystem and therefore less charcoal production/emission while the number of fires have probably increased with human ac-

tivity (Langevelde et al., 2003; Archibald et al., 2012). In the focus example (Fig. 4c “Shrubland”), Quick et al. (2018) assume that the Ellandvlei site experienced increased moisture availability in conjunction with warmer conditions from 1500 yr cal. BP. This increase in humidity contrasts with what was happening further north (Fig. 3d, green curve) but it could also be driven by climate variability (increased drought frequency), causing shifts in vegetation composition and increased fire activity, as suggested by Ekblom (2008) for coastal Mozambique during this period. A less fire-prone vegetation change may also explain that there is no strong relationship between population increase and a constant rate in sedimentary charcoal records (Fig. 3d).

4. Conclusions

Here we provide a continental-scale synthesis of charcoal-based paleofire reconstructions for the last 25,000 years in Africa. We show that before 5000 years, the trend in reconstructed biomass burning at the continental scale should be interpreted with caution due to the scarcity of data. For the last 5000 years, where the reconstructed trends are more reliable, the drivers of past fire activity seem to be more linked to changes in human activities than to climate variability. This long-term relationship is however modified by more recent use of fire. Indeed, following European colonization across Africa, fire suppression policies have disrupted local uses and practices of fire, leading to rapid and significant modifications to the long-term fire regime and resulting in shifts in ecosystem structure, composition, and functioning (Bond and Zaloumis, 2016; Moura et al., 2019). Paleofire reconstructions can therefore provide crucial baseline information to deepen our understanding of the relationships among fire, humans, vegetation and climate. These baselines can also help identify whether current fire policies fall within the historical range of variability of historical fire patterns (Gillson, 2021; Gillson et al., 2021), but there are still some limitations to the widespread application of charcoal-derived past fire regimes for fire management. As illustrated here, these data can only provide rough estimates of changes in biomass burning through time, which can be challenging to translate into actionable information for practitioners and other stakeholders. One way forward is to continue to develop robust calibration studies linking past and present in order to more precisely quantify regional paleofire reconstructions into metrics directly applicable to management (Hawthorne et al., 2018), including how a range of fire regimes directly impact vegetation recovery times.

Finally, to improve the quality and representativeness of paleofire studies, it is imperative that long-term analyses integrate paleofire reconstructions using adapted and homogenized methodologies. Particular emphasis should be placed on regions such as Western Africa where limited or non-existing fire history data poses a significant challenge. Therefore, our group aims at enhancing data across the continent and obtaining records for trends earlier than 5000 years, as well as applying more robust methods for homogenization of data across the continent.

Data availability

This study is based on the Global Charcoal Database (<https://database.paleofire.org>) developed by the Global Paleofire Working Group, currently managed by the International paleofire Network (<https://paleofire.org>) and hosted at the Maison des Sciences de l'Homme et de l'Environnement at University of Bourgogne Franche-Comté (France).

Uncited References

Cochrane and Schulze, 1999a; Cochrane and Schulze, 1999b.

CRedit authorship contribution statement

Laurent Bremond: Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Julie C. Aleman:** Writing – review & editing, Funding acquisition. **Charly Favier:** Writing – review & editing, Formal analysis. **Olivier Blarquez:** Resources. **Simon E. Connor:** Resources. **Carlos E. Cordova:** Writing – review & editing, Resources. **Colin Courtney-Mustaphi:** Writing – review & editing, Resources. **Abraham N. Dabengwa:** Writing – review & editing, Resources. **Graciela Gil-Romera:** Writing – review & editing, Resources. **William D. Gosling:** Writing – review & editing. **Tamryn Hamilton:** Resources. **Vincent Montade:** Writing – review & editing, Resources. **Andriantsilavo H.I. Razafimanantsoa:** Resources. **Mitchell J. Power:** Writing – review & editing. **Estelle Razanantsoa:**

Resources. **Ibouraïma Yabi:** Resources. **Boris Vanni re:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

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Appendix A. Supplementary data

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