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Fire and human management of late Holocene ecosystems in southern Africa

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Fire and human management of late Holocene ecosystems in southern Africa

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Abstract

Globally, fire is a primary agent for modifying environments through the long-term coupling of human and natural systems. In southern Africa, control of fire by humans has been documented since the late Middle Pleistocene, though it is unclear when or if anthropogenic burning led to fundamental shifts in the region's fire regimes. To identify potential periods of broad-scale anthropogenic burning, we analyze aggregated Holocene charcoal sequences across southern Africa, which we compare to paleoclimate records and archaeological data. We show climate-concordant variability in mid-Holocene fire across much of the subcontinent. However, increased regional fire activity during the late Holocene (~2000 BP) coincides with archaeological change, especially the introduction and intensification of food production across the region. This increase in fire is not readily explained by climate changes, but rather reflects a novel way of using fire as a tool to manage past landscapes, with outcomes conditioned by regional ecosystem characteristics.

Keywords: Paleofire, Food production, Southern Africa, Microcharcoal, Human-environment interaction

1. Introduction

Fire is a key determinant of ecosystem function worldwide (Bowman et al., 2009). Many ecosystems today (e.g., savannas and grasslands in tropical areas that could support forests) are a legacy of long-term fire activity and are unlikely to persist in its absence (Bond et al., 2005; Bowman et al., 2011), requiring consideration of fire history for their management (Keeley et al., 2011). In addition to natural sources of ignition, humans apply fire to modify environments across a range of ecological conditions and socioeconomic configurations (Butz, 2009; e.g. Codding et al., 2014; Nigh and Diemont, 2013; Roos et al., 2018). Burning vegetation can produce short-term gains such as flushing out game or clearing space for agricultural activities, and can also result in delayed benefits by improving the condition of the underlying soil, inducing vegetation growth, and influencing the kinds of organisms that recolonize burned areas. By mediating the climatic and biotic factors that determine primary productivity, anthropogenic burning can act as a means of augmenting productivity and/or mitigating risk in uncertain environments, while simultaneously influencing the character and resilience of ecosystems.

There has been considerable attention paid to the role of humans influencing fire regimes and the scale of their impact on ecosystems (Archibald et al., 2012; Bond and Zaloumis, 2016; Bowman et al., 2011). Human use of fire for landscape modification is an adaptation that potentially developed deep in the past (Brown et al., 2009; MacDonald et al., 2021); however, disentangling the signals of past fire used for resource management from naturally occurring fire is difficult (Bowman et al., 2011; Scherjon et al., 2015). This is especially true in southern Africa, which has one of the longest records of human-environment interactions in the world (Pyne, 2015). Ethnohistoric accounts attest to the use of fire by indigenous pastoralist communities within the last few hundred years (Pooley, 2014), and it has long been assumed that prehistoric human populations would also have used fire to improve the productivity of their environments (Deacon, 1993; Huffman, 2007), but evidence for intentional landscape burning deeper in time is lacking.

With this in mind, we present data from the Holocene of southern Africa to address this long-standing problem in the history of human-environment interactions. Charcoal influx in sedimentary sequences from across the subcontinent provides evidence of broad-scale burning, while summed probabilities of radiocarbon determinations from archaeological contexts indicate relative changes in the intensity of human activity. Paleoclimate reconstructions drawn from multiple proxies are used to identify coeval patterning in aridity, allowing us to compare periods of fire-prone conditions in southern Africa with the record of past fire activity.

2. Climatological, ecological and archaeological context

The diverse environments of present-day southern Africa are shaped by contrasting rainfall regimes (**Fig. 1**A). Precipitation in much of eastern and central southern Africa is controlled by advection of moisture from the Indian Ocean, bringing monsoon rains concentrated in the austral summer months (the summer rainfall zone or SRZ), while the southwest has a Mediterranean climate featuring winter rainfall brought by south Atlantic westerlies (the winter rainfall zone or WRZ) (Tyson, 1986). In the boundary between these two regions, and extending along a narrow strip of the southern coastline, is a mixed

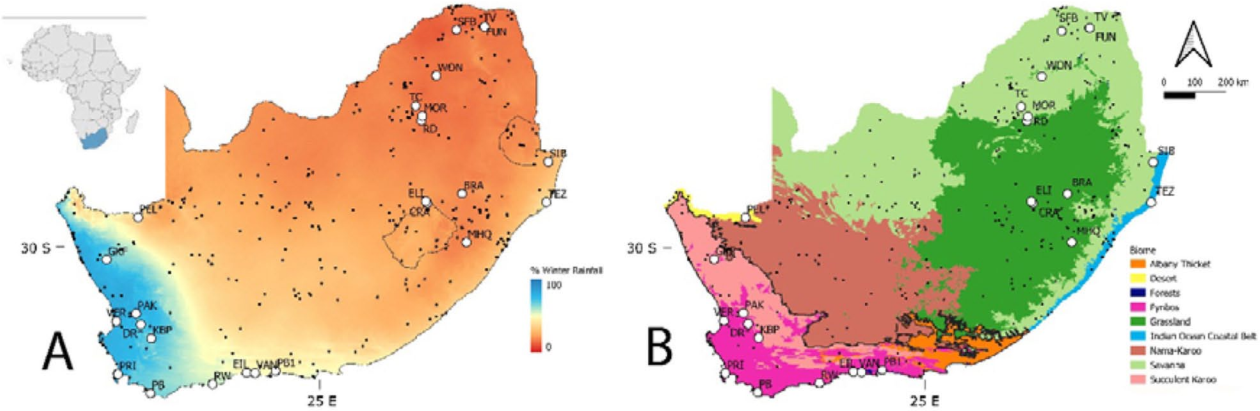

Fig. 1. Locations of sediment cores (open circles) and radiocarbon determinations from archaeological sites (black dots) in southern Africa. A) rainfall seasonality expressed as the percentage of rainfall occurring during southern hemisphere winter months (June–August), B) contemporary vegetation biomes, with heavy black line showing approximate extent of Greater Cape Floristic Region. Core labels correspond with SI Table 1. Data (Abatzoglou et al., 2018; Rutherford et al., 2006).

regime where rainfall is distributed more evenly throughout the year (the aseasonal zone or ARZ). Over millennial timescales, the SRZ and WRZ are typically out of phase, such that wetter conditions in one area often coincide with drier conditions in the other (Chase et al., 2017). Although the spatial extents of the different rainfall zones have likely varied through time and there is growing awareness of climatic variability within these regions (Chase et al., 2020), these general distinctions are thought to have persisted since the Pliocene (Lehmann et al., 2016).

These climate regimes contribute to striking differences in vegetation that have implications for the likelihood of ignition and the availability of suitable fuels for fire (Fig. 1B). Many of the plant communities in southern Africa are fire-adapted and require burning to limit the expansion of forests and maintain the structure of meta-communities (Bond et al., 2003; Thuiller et al., 2007). The eastern half of southern Africa is dominated by Savanna and Grassland biomes. While ignition in this region is more likely during the dry season, burning is typically fuel-limited, and larger fires coincide with build-up of burnable biomass during wetter time periods (Daniau et al., 2013). The western and southern coasts and adjacent inland areas along the Cape

Fold mountain ranges are home to the Greater Cape Floristic Region (GCFR), a phytogeographic region distinguished by hyperdiverse fynbos, renosterveld, and succulent karoo plant communities (Bergh et al., 2014). Fire in the region is limited at one end of the aridity spectrum by low fuel connectivity and biomass, and on the other by low susceptibility to ignition, with the most fire prone vegetation communities existing between these two extremes (Gillson et al., 2020). Burning in fynbos systems is not necessarily fuel-limited (van Wilgen, 2009), and relationships between vegetation age structure and fire size are complex. In general, larger fires in the GCFR tend to correlate with drought conditions, though seasonality varies across the region (Kraaij and Van Wilgen, 2014).

In addition to the influences of climate and vegetation, there is also an extensive history of anthropogenic fire in southern Africa. Intentional use of fire by humans is documented from the late middle Pleistocene by the presence of in-situ hearths (Deacon, 1995), heat-treated stones (Brown et al., 2009), charred food remains (Larbey et al., 2019; Wadley et al., 2020a), and use of ashes in bedding (Wadley et al., 2020b). In a review of ethnographic cases, Scherjon et al. (2015) demonstrated that foraging populations use fire in a number of different ways, including manipulating vegetation and fauna, hunting, and communication. Such activities may have intentional and unintentional consequences for the ecosystems they inhabit (Bird et al., 2020). Food production practices arrived from the north beginning in the late Holocene. In summer rainfall regions, incoming farmers introduced a mixed economy that included cultivation of crops (principally sorghum and millet), keeping of domestic animals, iron smelting, and settled village life (Mitchell and Whitelaw, 2005; Parkington and Hall, 2010). In winter rainfall regions of the west, domesticated grains could not be grown without irrigation, so farming was limited to pastoralism. The appearance of domesticated species in faunal assemblages, dating to around 2000 BP (Coutu et al., 2021; Sealy and Yates, 1994), is also associated with archaeological signals including ceramics and new stone tool technologies (Lander and Russell, 2018), isotopic evidence for dietary change (Sealy, 2010), and genetic signals among descendant populations for lactase persistence and known pastoralist lineages (Uren et al., 2016). The relative timing of these signals is debated, and their expression is not monolithic across southern

Africa; however, in most cases this period is marked by the introduction of domestic stock-keeping, a practice that has been associated with novel human-environment interactions (Smith and Zeder, 2013). In pastoralist systems today, fire is used principally to clear unwanted vegetation or pests, improve the quality of forage, and reduce the risk of dangerous wildfires (Butz, 2009), and historic accounts indicate that similar practices were in use in southern Africa at the time of European contact (Pooley, 2014; Skead, 2009).

In this study, we seek to explore the drivers of fire in southern Africa and the role, if any, of past human ecosystem management. Fire activity attributed to anthropogenic sources should occur independently of shifts in local conditions that might produce similar patterning without human intervention (Bird and Cali, 1998; Thompson et al., 2021). Given the contrasting range of conditions for fire across southern Africa, especially the anti-phase relationship between precipitation in the western and eastern sub-regions, we expect that combined archives of fire activity will fail to show a coherent signal when fire systems are controlled predominantly by climate. Likewise, we expect few instances where signals in the western and eastern areas demonstrate coordinated change in fire activity under a climate-driven scenario. Here, we focus on the Holocene, which encompasses a long period of forager and a known shift in land use and subsistence practices with the advent of farming in southern Africa ~2000 BP (Mitchell, 2002).

3. Materials and methods

3.1. Microcharcoal analyses standardization approach

Sedimentary microcharcoal analysis was used in this study to assess the history of fire activity in southern Africa. Charred particles are produced through incomplete combustion of organic matter. These are transported away from points of combustion by wind or water and collect in sedimentary basins. Sequential sediment deposition in these basins produce laminar sedimentary records, which are then sampled using various methods (e.g. coring, section sampling, etc.). Charcoal recovered from sedimentary records provides direct evidence of biomass burning over time.

Charcoal quantities are typically reported as a range of metrics, including influx, concentration, charcoal/pollen ratios, gravimetrics, image analysis, size classification etc. Previous charcoal syntheses (Power et al., 2008) reveal that values from individual sedimentary-based charcoal sample range over 13 orders of magnitude. A protocol has been established for transforming and standardizing individual charcoal records. The protocol includes: (1) rescaling the values using a minimax transformation, (2) transforming and homogenizing the variance using the Box-Cox transformation, and (3) rescaling values once more to z-scores (see SI Appendix 1 for full details).

Charcoal data from lacustrine and terrestrial sources was obtained from the Global Charcoal Database (www.paleofire.org), National Centers for Environmental Information (www.ncei.noaa.gov), and additional published sources (Chase et al., 2015b; Neumann et al., 2011; Quick et al., 2016). These are distributed in two clusters: one in the southwest corner of South Africa, the other more widely spread in the northeast (Fig. 1). Data were transformed and standardized using the paleofire software package (Blarquez et al., 2014) for the R statistical computing platform (R Development Core Team, 2017).

3.2. Radiocarbon analysis

To assess human occupation history, summed probability distributions (SPDs) were generated using radiocarbon determinations from archaeological surveys and excavations. These methods use the frequency of dated cultural materials recovered by archaeologists as a model for the depositional history of these kinds of materials overall (e.g., Riris and Arroyo-Kalin, 2019). Assuming that the record is not systematically biased by sampling, processing, preservation, visibility, etc. at the scale of observation, this method provides broad indications of the relative intensity of human activity over time.

Radiocarbon determinations were drawn from the Southern African Radiocarbon Database (https://c14.arch.ox.ac.uk/sadb), a collection of data from previously published sources (Loftus et al., 2019). In our study, analyses were limited to data from the last 10,000 years from Eswatini, Lesotho, and South Africa (n = 1845). Analyses were undertaken using the rcarbon v1.3 software package (Bevan et al., 2019) for the R statistical computing platform (R Development Core

Team, 2017). We follow contemporary best practices to estimate sensitivity to parameter choices and characterize uncertainty and potential sources of bias, with details provided in SI Appendix 2.

4. Results

Composite microcharcoal records are an indicator of the relative degree of fire activity among the depositional environments under study (Power et al., 2008). Experimental studies have shown that while the frequency of larger charred particles is usually indicative of local fire events, smaller particles (e.g. <100 mm) are more reflective of extralocal or regional trends in "background" fire activity (Whitlock and Anderson, 2003). We used 27 sedimentary sequences from 25 sampling sites for building composites, derived from lacustrine/estuarine cores and rock hyrax (*Procavia capensis*) midden (hyraceum) deposits (Table S1). These are distributed in two clusters: one in the west (mostly inside the WRZ/ARZ and the GCFR), the other in the east (inside the SRZ and the Grassland/Savanna biomes; see Fig. 1). These clusters provide a convenient point of distinction because, as discussed above, there are notable differences in the climate, vegetation, and archaeological histories of the eastern and western parts of the subcontinent.

When records from across southern Africa are aggregated (**Fig. 2**A), they show a peak in charcoal influx in the early mid-Holocene (~8200) years ago, followed by short-term fluctuations over the next ~6000 years, with higher degrees of uncertainty around most peaks. For example, the period between 7000 and 5000 BP has a median value close to zero, with confidence intervals extending between +0.5z and −0.5z. This suggests contrasting values are contributing to the aggregate picture during this period. There is an increase in fire activity just before 2000 years ago, after which fire activity is persistently higher than average. Separating this sample into eastern and western subsets (Fig. 2B and C), the two records are divergent through much of the mid-Holocene (Fig. 2D). Notably, higher levels of fire activity in the west between 7000 and 5000 BP contrast with lower levels in the east, consistent with climatic and environmental differences between these two regions and helping to explain the uncertainty during

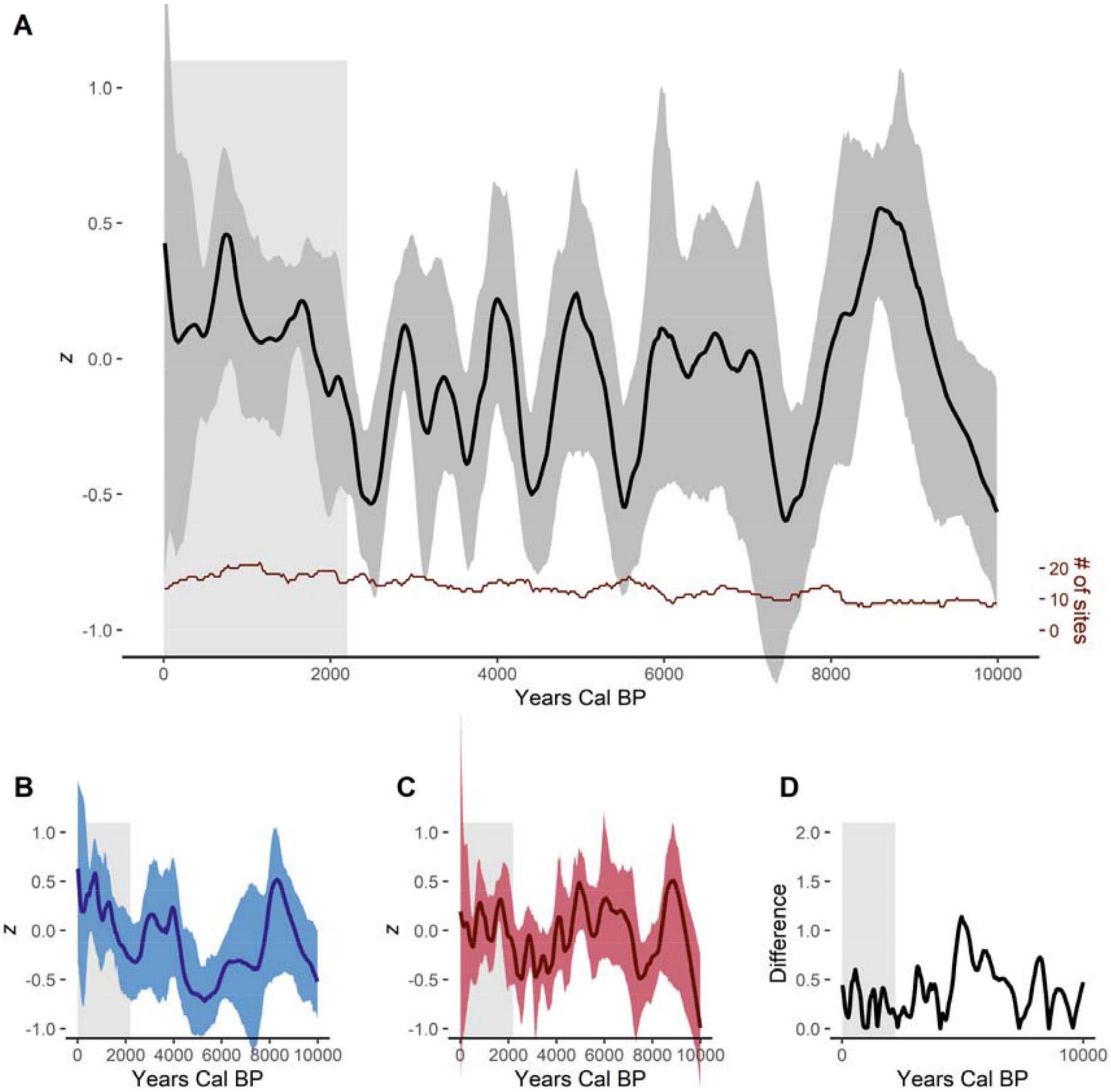

Fig. 2. Holocene composite charcoal influx (z) for A) southern Africa, B) eastern subset, C) western subset, and D) difference plot between eastern and western subsets. Solid lines in A, B, and C indicate median composite influx values with LOWESS smoothing (250-year half-width); envelopes indicate 95% confidence intervals. Dark red line in A shows number of sites contributing to the charcoal influx record over time (see Fig. S1 for sample density). Light grey area in all plots indicates onset of novel subsistence strategies, defined here using the earliest dated archaeological instances of domesticated stock (Lander and Russell, 2018).

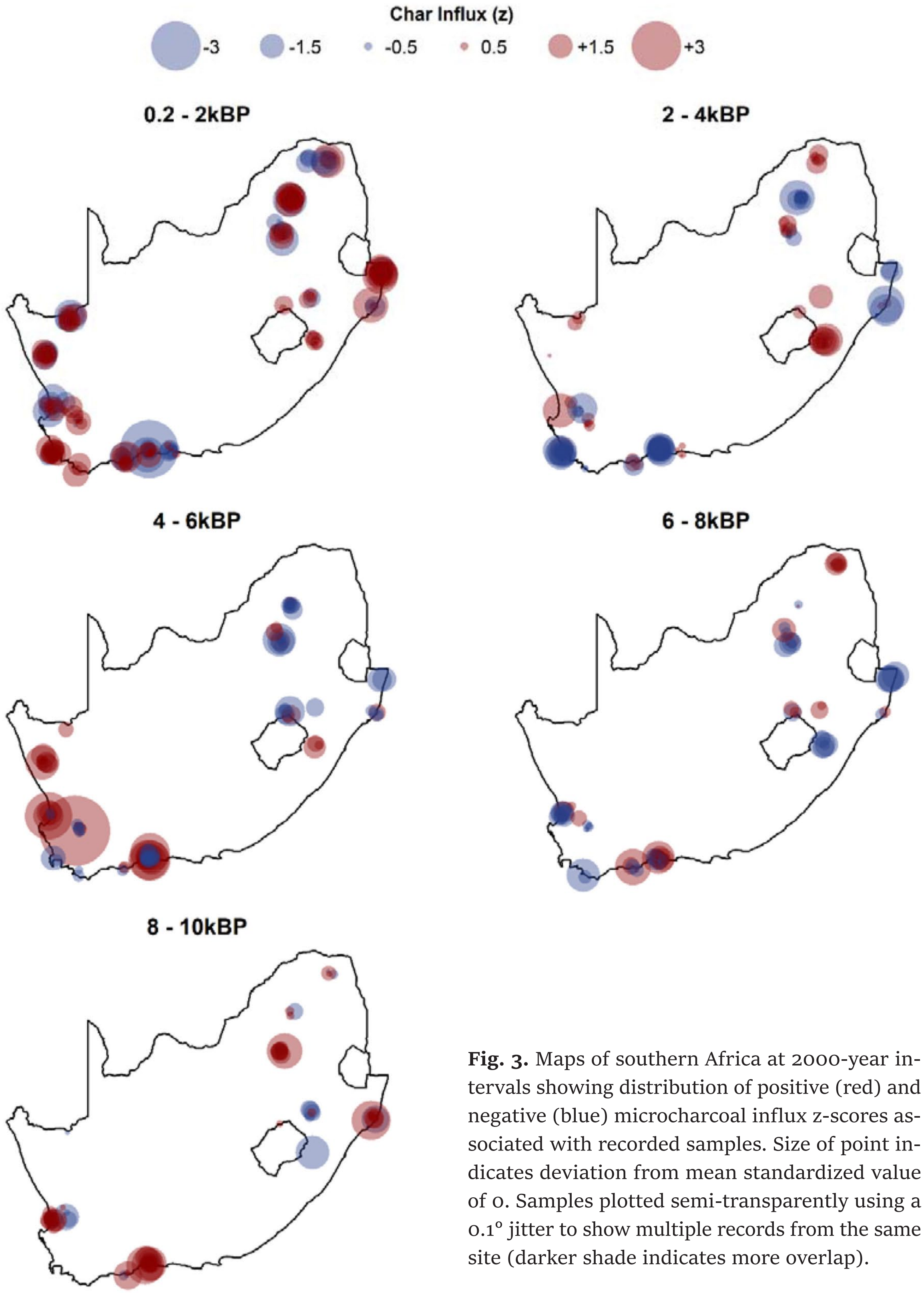

Fig. 3. Maps of southern Africa at 2000-year intervals showing distribution of positive (red) and negative (blue) microcharcoal influx z-scores associated with recorded samples. Size of point indicates deviation from mean standardized value of 0. Samples plotted semi-transparently using a 0.1° jitter to show multiple records from the same site (darker shade indicates more overlap).

this period in the aggregate record. Increases in fire activity during the early and late Holocene persist in both records, though the eastern subset is especially anomalous.

These shifts in fire activity can be further illustrated by exploring the spatial distribution of charcoal influx at the individual sampling sites across southern Africa (**Fig. 3**). To do this, we calculated transformed z-scores for microcharcoal abundances in each dated record within those sites (see SI Appendix 1 for details). These z-scores were then plotted in 2000-year intervals according to direction and degree of deviation from 0. It is important to clarify that negative and positive values are not indicative of absence or presence, but that the influx is less or more than that recovered on average from that site during the base period (10,000–200 BP).

The mapping exercise shows interregional coherence in the earliest period (10-8k BP) that is replaced by a shift toward more fire activity in the west relative to the east, especially between 6 and 4k BP. This trend is reversed between 4 and 2k BP, with marginally increased fire activity in the east and a decline in the west. The final time window (2000–200 BP) shows the greatest distribution of positive fire records; of sites with records from this period (N = 24), 82.5% indicate positive influx and 62.5% show net positive anomalies. Using a two-sample Kolmogorov-Smirnov test between influx values before 2000 BP (n = 591) and after 2000 BP (n = 320) suggests that the pattern seen in the map is not an artifact of improved sampling resolution over time (D = 0.124, p = 0.003). Additional one-sample tests were used to evaluate the significance of deviations between the influx scores in each time window and the standard normal distribution. Only the 2k – 200 BP window (D = 0.096, p = 0.012) featured a significant positive shift (m = 0.13). It follows that the late Holocene trend is not just localized to a single region in southern Africa, but is reflecting increases in fire activity within regions and between them.

The observed changes in fire occurrence during the last 10,000 years, and their periodic coordination across southern Africa, cannot readily be explained by changes in climate using currently available records. In the east, where nearly half of our charcoal samples occur, the early-to-mid Holocene fire record follows closely with aridity indices derived from pollen sequences (**Fig. 4**A–B) (Chevalier

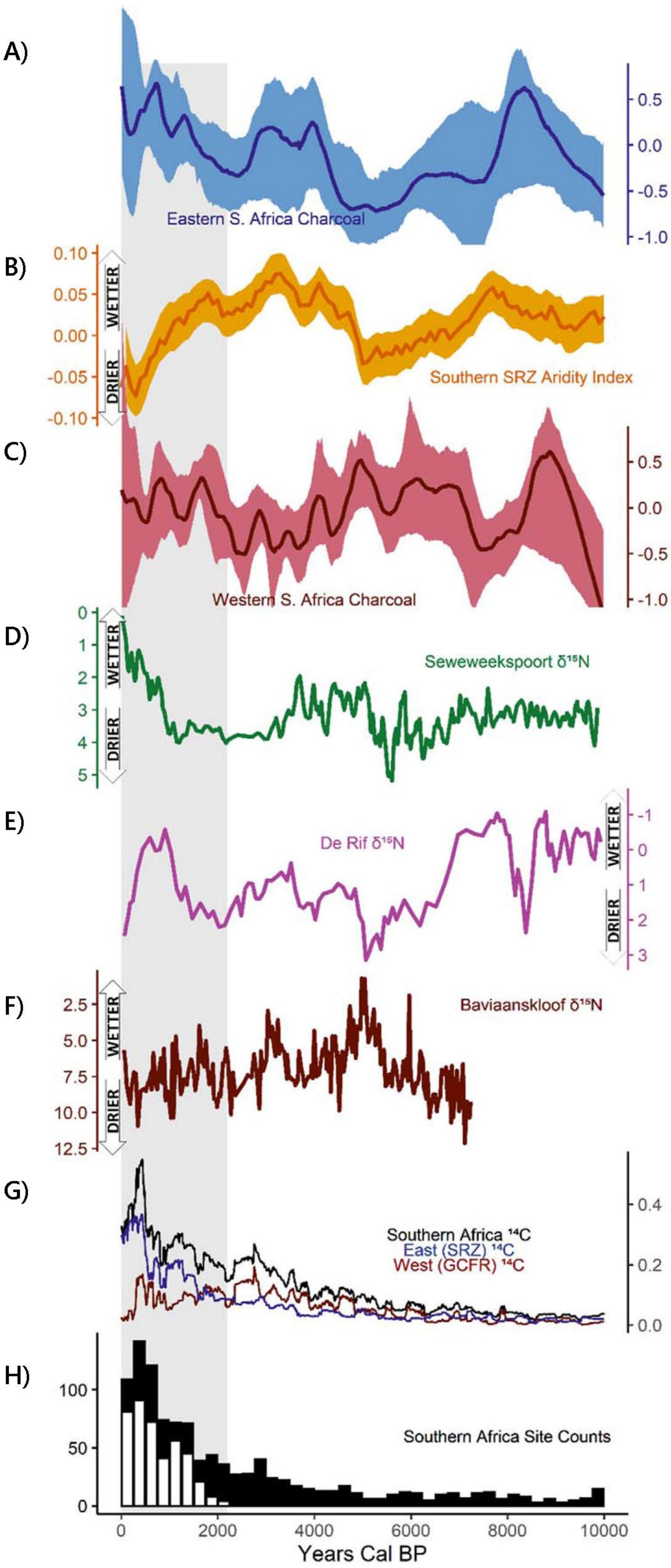

Fig. 4. Comparison of

(A) composite charcoal from eastern southern Africa,

(B) pollen-derived aridity index from the southern SRZ (Chevalier and Chase, 2016),

(C) composite charcoal from western southern Africa

(D–F) hyraceum nitrogen isotope concentrations from sites across the GCFR (Chase et al., 2011, 2013, 2020), and

(G) summed probabilities of radiocarbon determinations from all southern Africa (black), SRZ (blue), and GCFR (red), and

(H) counts of all dated archaeological sites (black bars) and sites associated with pastoralism (white bars) from southern Africa.

Light grey area in all plots indicates onset of novel subsistence strategies, defined here using the earliest dated archaeological instances of domesticated stock (Lander and Russell, 2018).

and Chase, 2016). This implies more fire when there is greater moisture availability, consistent with a fuel-limited fire regime (Daniau et al., 2013). However, an increase in aridity is indicated over the last 2000 years that would be expected to drive a decrease in fire, in direct contrast to the substantial increase observed in charcoal influx (Chevalier and Chase, 2016). In the west there is an emerging picture of regional heterogeneity in Holocene climate patterns that suggests spatially varying influences (Chase et al., 2019). For example, proxies for moisture availability in the ARZ vary markedly along east-west and elevational clines, potentially indicating differing influences of Atlantic and Indian Ocean systems (Chase and Quick, 2018). While paleoclimate records sampled across this part of the subcontinent show marked changes in moisture availability earlier and later in the Holocene, these vary from place to place, and there is little in the climate record consistent with directional fire regime change around 2000 years ago (Fig. 4D–F).

Increased evidence for fire could reflect a broad shift in human activity, such as a change in the overall population or a behavior that is associated with increased burning. Changes in the density of probabilities from archaeological radiocarbon determinations are increasingly used as a proxy for human activity (Riris and Arroyo- Kalin, 2019; Timpson et al., 2014). This method rests on assumptions about the sampling, visibility, and preservation of datable archaeological materials, and is subject to known biases in the radiocarbon calibration process (discussed in more detail in SI Appendix 2). Like the microcharcoal record, the collection of radiocarbon data in southern Africa is uneven in time and space; however, it is presently the most coherent dataset available for identifying broad trends in the intensity of human activity at regional and subcontinental scales. Summed probability distributions (SPD) were generated using 1845 determinations from 514 unique sites across southern Africa (Fig. 1). The overall trend shows increases through time (Fig. 4G black line), with similar patterning visible in counts of dated archaeological sites over time (Fig. 4H). However, the rate of change is notably different between eastern and western areas (Fig. 4G blue and red lines). The former shows continuous growth during the late Holocene, while the latter features more gradual growth that becomes effectively static over the last 2000 years (see also SI Fig. 9).

5. Discussion

Southern Africa's contrasting climate configurations allow for demonstration of human influence on systems where fire has consistently been a primary force shaping the environment. Evidence for fire activity aggregated across the subcontinent shows fluctuations during the mid-Holocene align with predominant climate regimes that enable ignitions and control fuel availability, as would be expected in predominantly fuel-limited systems. Increases in the years around and after 2000 BP deviate from this trend (Fig. 2A), coinciding with the new subsistence strategies through the region that brought fundamental changes to human–environment interactions (Bousman, 1998; Lander and Russell, 2018; Sealy, 2010). Our study provides empirical evidence for a widespread connection between food production and novel fire regimes in southern Africa. At the same time, the contributions to this pattern differ between eastern and western regions, suggesting subtleties in the ecological scales of human impacts (Power et al., 2018), and we consider these below.

In grasslands and savannas of eastern southern Africa, changes in microcharcoal deposition show clear distinctions between periods of greater or lesser fire activity. During the last 2000 years, increased fire activity occurs in contrast to prevailing climate-fire dynamics, suggesting an alternative driver is generating more microcharcoal than would be expected from natural ignitions alone. This increase coincides with a positive rate of change in proxies for human activity such as radiocarbon summed probability distributions and site counts, in accord with established associations between human presence and fire activity (Marlon et al., 2013). These increases in evidence for fire and human activity also coincide with the advent and proliferation of new methods of food production; here, mixed farming practices. We argue this patterning in the late Holocene microcharcoal record is explainable as the outcome of a feedback loop in a coupled natural-human system (Liu et al., 2007), where burning produces outcomes that enable or encourage additional burning. Burning in these environments maintains the distribution of palatable grasses, reduces the encroachment of woody species and, outside of arid areas, may increase above-ground productivity (Little et al., 2015; Oluwole et al., 2008; Trollope et al., 2014). Since grasses in many environments can be burned regularly (~1–4 years) (Morris et al., 2021; Oluwole et al., 2008), human managers are able to exert substantial control over the distribution of resources across the landscape, enabling longer-term residence and more concentrated human activity (Bird et al., 2020; Boivin et al., 2016), and further increasing the benefit of, and capacity for, burning activity. These effects presumably would have been familiar to early farmers whose practices originated in northern areas and dispersed along grassy corridors (Chritz et al., 2015), and such regimes may have been further augmented by fire used to clear land for planting and grazing.

In the western areas of southern Africa, the aggregate microcharcoal record also indicates a modest increase in fire activity during the late Holocene, but transitions in this record throughout the Holocene are less clear when compared with the eastern areas. The GCFR has many fire-dependent species, and there has been plenty of speculation concerning the role of anthropogenic fire in the maintenance of vegetation community structure (Bond et al., 2003; Deacon, 1993; Pyne, 2015). However, if a process of intensive burning and grazing were initiated in the west, it is questionable whether it would be sustainable for long periods of time. Most fynbos-dominated habitats consist of low-nutrient vegetation and are unlikely to have supported high densities of large herbivores. While consumption of fynbos by grazers is typically limited to post-fire growth (Luyt, 2005), sustainable fire return intervals are typically less frequent in fynbos systems (~10–20 years for fynbos, ~3–7 years for renosterveld) (Kraaij and Van Wilgen, 2014; Rebelo et al., 2006). Renosterveld communities were more widespread in the past (Rouget et al., 2006), and it has been suggested on the basis of historical records that they may have had a grassier character as well (Rebelo et al., 2006 cf. Forbes et al., 2018), providing more grazing opportunities than present vegetation distributions. However, there is evidence to suggest that fire coupled with grazing in renosterveld can diminish palatable species, converting grazing lawns into unpalatable shrubland (Radloff et al., 2014). This would imply that the use of fynbos or renosterveld for grazing livestock may have required more nuanced management dependent on place-specific conditions, potentially limiting the feedback capacity for an incoming food production system and making it more difficult to distinguish from natural fire regimes in a microcharcoal record.

The complex interrelationships between climate, vegetation, and fire, and their influence on different forms of economic organization, deserve more attention.

In addition to differences in vegetation responses to anthropogenic firing when compared to eastern areas, there is also greater variability within the western areas in terms of rainfall seasonality and vegetation community structure that might influence the magnitude of changes in the aggregate microcharcoal record. This can be illustrated by contrasting the Verlorenvlei and Eilandvlei sampling sites, both of which are coastal lakes considered to lie within the GCFR (Bergh et al., 2014). Verlorenvlei is situated on the semiarid western coast, receiving 200–250 mm of rain per annum almost exclusively during the winter, and vegetation consists of sandplain and mountain fynbos as well as coastal strandveld (fynbos-succulent karoo mosaic). These communities are flammable, though fire in strandveld is limited by succulent content and lower fuel connectivity (Kraaij and Van Wilgen, 2014). Eilandvlei is located on the southern coast in the ARZ, receiving 900–1000 mm of rain per annum. This site lies within a fynbos-forest mosaic that is generally less susceptible to burning due to lower probability of ignition (MacPherson et al., 2019). During the last 2000 years, Verlorenvlei shows signals like many other western sites, with a modest increase in the number of positive fire anomalies (SI Fig. 2). Such patterning might be expected from the introduction of grazing in a system with limited opportunities for positive feedbacks (see also Cordova et al., 2019; MacPherson et al., 2018). Eilandvlei, on the other hand, stands out with high ratio of negative anomalies during this period, consistent with pollen evidence showing increasingly wet conditions and a growing forest component (Quick et al., 2018). As opposed to the eastern half of the subcontinent, where areas with climatic and vegetation differences are mostly unified by consistent rainfall seasonality and a grassy component, the diverse climate and vegetation arrangements across the GCFR exert contrasting controls on fire and are therefore less likely to exhibit a uniform fire response through time when aggregated. More sampling across this region would be helpful for disentangling fire signals, particularly among the different vegetation communities of the GCFR (e.g., forest-fynbos mosaic vs. strandveld) and across the WRZ/ARZ divide.

Prior to 2000 years ago, the southern African record of fire activity and its connections to humans and climate are less clear. A peak in the composite charcoal record occurs before 8 kya (Fig. 2A), a pattern that occurs in both subsets and is also observed across sub-Saharan Africa more broadly (Marlon et al., 2013). The coincidence of these fire signals across seasonal rainfall zones is suggestive of a coordinating process. A potential explanation for this is the 8.2k climate anomaly (Alley and Ágústsdóttir, 2005), a global cooling event which may have accentuated fire-positive conditions across southern Africa (Chase et al., 2015a; Voarintsoa et al., 2019). Fluctuations in the composite microcharcoal record during the mid-Holocene are likely an outcome of western and eastern climate regimes exerting contrasting influences through time (Fig. 2A–C). When broken down into sub-regions, these exhibit an antiphase relationship consistent with the overall climatology. These factors suggest climate was likely a driving factor throughout the early to mid-Holocene, but other factors could also contribute to changes in fire activity during this period. Charred traces of geophytes (e.g. Moraea spp., Watsonia spp.) found in Middle and Later Stone Age archaeological deposits in southern Africa (Liengme, 1987; Wadley et al., 2020a) suggest a long-term role in subsistence (Marean, 2010). Connections between fire and geophyte productivity have been used to argue that earlier populations may have used fire to increase the abundance and predictability of these resources (Botha et al., 2020; Deacon, 1993). If this kind of manipulation of vegetation were occurring, though, it is difficult to detect in the composite microcharcoal record. This may speak to the relative densities of forager populations and scales of burning activities practiced by foragers compared to food producers (Nikulina et al., 2022; Roos et al., 2018; Scherjon et al., 2015).

Understanding human impacts on past vegetation communities has implications for the management of contemporary communities descended therefrom. For example, many ecosystems in southern Africa are maintained by regimes of regular disturbances (e.g., Morris et al., 2021; Gillson et al., 2020), and fire is frequently used as a management tool for biodiversity conservation (e.g., van Wilgen, 2013; van Wilgen and Forsyth, 2011). Historical records of fire activity provide insights into these dynamics and inform management practice, but such records are limited in temporal extent (typically decades) and are frequently derived from observations in ecosystems that have been heavily altered by recent human activities (e.g., introduction of invasive species, landscape fragmentation). It follows that maintaining biodiversity and enhancing ecosystem services may require disturbance frequencies or intensities that extend beyond the scope of historically recorded regimes (Case and Staver, 2017). Information from paleoecological archives such as those presented here can be helpful in establishing longer-term baselines. Our observations imply a deep history of human-mediated fire activity that merits consideration when evaluating 'natural' fire regimes across the biomes of southern Africa.

In summary, it has long been presumed that fire was used to manage the landscapes of southern Africa in the past. While our analysis shows various couplings between climate and fire activity in southern Africa during the Holocene, we argue that an increase in fire activity during the last 2000 years, particularly in eastern areas, is likely associated with the spread of food production. However, the character of local vegetation and its constraints on the benefits realized from anthropogenic burning contribute to the patterning observed in the record. The result is a signal that is not uniform across southern Africa, and likely to be different still in other ecosystems through which food production dispersed. These interrelationships between vegetation, climate, and fire are fundamental both for evaluating narratives of human history and for understanding the role of past human activity in shaping present day ecosystems.

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Data availability Code used to produce the figures in the manuscript and supplementary information can be found at https://doi.org/10.5281/zenodo.6612515 . This study makes use of previously published data. Data sources have been identified in the supplementary information and are also available in the code repository.

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article follows the **References** and is also attached to the repository record at https://digitalcommons.unl.edu/natrespapers/ .

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Supplementary Information: Fire and the management of late Holocene landscapes in southern Africa

Appendix 1: Microcharcoal analysis

Method description

Sedimentary microcharcoal analysis was used in this study to assess the history of fire activity in southern Africa. Charred particles are produced through incomplete combustion of organic matter (Scott 2010). These are transported away from points of combustion by wind or water and collect in sedimentary basins. Sequential sediment deposition in these basins produce laminar sedimentary records, which are then sampled using various methods (e.g. coring, section sampling, etc). These records are affected by biophysical factors, including (but not limited to) fuel type, fire size, catchment size, rate of sedimentation, preservation, etc (Patterson et al. 1987; Gardner and Whitlock 2001). Despite these factors, charcoal recovered from sedimentary records have been shown to provide robust evidence of biomass burning over time (Whitlock and Larsen 2002; Power et al. 2008; Marlon et al. 2013).

Data sources

Microcharcoal data was obtained from the Global Charcoal Database (www.paleofire.org; Power et al. 2010), National Centers for Environmental Information (www.ncei.noaa.gov), and additional published sources (SI Table 1). Records (*n*=27) and their characteristics are presented in SI Table 1.

SI Table 1: Charcoal data sources. Latitude/Longitude given as decimal values. Asterisk (*) indicates sites with multiple sediment samples.

Site	Latitude	Longitude	Elevation (masl)	Annual Precipitation (mm)	Type	Subset	Source	Map label
Braamhoek	-28.23	29.58	1700	770.45 ± 129.9	Wetland	EAST	Norström et al. 2009	BRA
Craigrossie	-28.54	28.46	112	750.73 ± 142.93	Wetland	EAST	Scott 1989	CRA
Elim	-28.48	28.41	1757	746.09 ± 143.83	Wetland	EAST	Scott 1989	ELI
Funduzi	-22.86	30.3	429	1113.94 ± 301.81	Lacustrine	EAST	Scott 2002	FUN
Lake Sibaya	-27.21	32.61	20	748.12 ± 166.93	Lacustrine	EAST	Neumann et al. 2008	SIB
Lake Teza	-28.51	32.3	8	1221 ± 237.24	Lacustrine	EAST	Scott and Steenkamp 1996	TEZ
Mahwaqa	-29.79	29.72	1800	994.52 ± 150.89	Wetland	EAST	Neumann et al. 2014	MHQ
Moreletta Stream	-25.73	28.3	417	668.69 ± 132.95	Wetland	EAST	Scott 1984	MOR
Rietvlei Dam	-25.88	28.27	112	684.03 ± 133.98	Terrestrial	EAST	Scott and Vogel 1983	RD
Scot's Farm Borehole 1	-22.96	29.4	823	552.76 ± 124.37	Wetland	EAST	Scott 1982b	SFB
Tate Vondo	-22.86	30.31	880	1113.94 ± 301.81	Wetland	EAST	Scott 1987	TV
Tswaing Crater	-25.41	28.08	1060	579.32 ± 113.36	Lacustrine	EAST	Scott 1999	TC
Wonderkrater borehole 3	-24.43	28.75	1100	534.23 ± 98.33	Wetland	EAST	Scott 1982a	WON
De Rif-1	-32.45	19.22	1151	311.54 ± 74.98	Terrestrial	WEST	Quick et al. 2011	DR*

De Rif-2	-32.45	19.22	1151	311.54 ± 74.98	Terrestrial	WEST	Quick et al. 2011	DR*
Eilandvlei	-34	22.63	5	555.03 ± 112.53	Lacustrine	WEST	Quick et al. 2018	EIL
Groenkloof	-30.35	18.12	1256	236.36 ± 69.14	Wetland	WEST	Macpherson 2016	GKF
Katbakkies Pass	-32.89	19.56	1170	267.67 ± 57.56	Terrestrial	WEST	Chase et al. 2015	KBP
Pakhuis Pass	-32.1	19.01	460	270.51 ± 66.6	Terrestrial	WEST	Scott and Woodborne 2007	PAK
Pearly Beach	-34.67	19.52	5	508.77 ± 89.31	Wetland	WEST	Quick et al. In press	PB
Pella 1_1	-29	19.14	490	83.61 ± 33.35	Terrestrial	WEST	Lim et al. 2016	PEL*
Pella 1_4a	-29	19.14	490	83.61 ± 33.35	Terrestrial	WEST	Lim et al. 2016	PEL*
Platbos 1	-33.94	23.57	258	758.97 ± 142.56	Wetland	WEST	Macpherson 2016	PB1
Princessvlei	-34.05	18.48	6	538.57 ± 108.56	Wetland	WEST	Neumann et al. 2011	PRI
Rietvlei Wetland	-34.37	21.53	17	435.36 ± 94.2	Wetland	WEST	Quick et al. 2015	RW
Vankervelsvlei	-34.01	22.9	153	632.07 ± 123.71	Wetland	WEST	Quick et al. 2016	VAN
Verlorenvlei	-32.35	18.43	20	242.99 ± 56.58	Lacustrine	WEST	Baxter 1997	VER

Analysis

Data were transformed and standardized using the paleofire software package for the R statistical computing platform (Blarquez et al. 2014). Charcoal quantities are typically reported as a range of metrics, including influx, concentration, charcoal/pollen ratios, gravimetrics, image analysis, size classification etc. Previous charcoal syntheses (Power et al. 2008; 2010) reveal that values from individual sedimentary-based charcoal sample range over 13 orders of magnitude. A protocol has been established for transforming and standardizing individual charcoal records. The protocol includes: (1) rescaling the values using a minimax transformation, (2) transforming and homogenizing the variance using the Box-Cox transformation, and (3) rescaling values once more to z-scores.

The minimax transformation rescales charcoal values from a particular record to range between 0 and 1 by subtracting the minimum charcoal value in the record from each charcoal value, and dividing by the range of values:

$$c_i' = \frac{(c_i - c_{min})}{(c_{max} - c_{min})}$$

where c_i' is the minimax-transformed value of the i^{th} sample in a particular record (c_i), and c_{max}, and c_{min} are the maximum and minimum values of all instances of c. The minimax transformation does not impact the distribution of the values or influence the pattern of variability over time for any particular record. Critically, the minimax-transformation allows records with value ranges at different orders of magnitude to be compared using a common scale. Charcoal values are typically skewed in their distribution, showing a long, or heavy, upper tail, and producing a disproportionate number of negative anomalies (or deviations from the mean of a particular base period) without further transformation. The rescaled values were then transformed using the Box-Cox transformation:

$$c_i^* = \begin{cases} \left((c_i' + \alpha)^\lambda - 1\right)/\lambda, & \lambda \neq 0 \\ \log(c_i' + \alpha), & \lambda = 0 \end{cases}$$

Where c_i^* is the transformed value, λ is the Box-Cox transformation parameter and α is a small positive constant (here, 0.01) added to avoid problems when c_i' and λ are both zero. The transformation parameter λ is estimated by maximum likelihood using the procedure described by Venables and Ripley (2002, p. 171). In practice, the optimization involved in selecting λ can be seen as an attempt to produce data values that are normally distributed, minimizing or eliminating unusual or outlying points. The Box-Cox transformation is also considered a variance-stabilizing transformation because it usefully reduces the dependence of variability in the data on the level of the values (see Emerson and Stoto, 1983). Box-Cox transformations of both the “raw” (e.g. influx or concentration data) and minimax-rescaled data, generates identical results. Because the specific combination of values being transformed and the transformation parameter λ can result in negative values in the transformed data, and because such values may seem counterintuitive, the transformed data can be rescaled again using the minimax transformation.

Often, paleo time series that are expressed as anomalies or deviations from some long-term average provide a useful context for interpreting past environmental change. The conventional approach to create such anomalies is to standardize the data, expressing the values as *z*-scores,

$$z_i = \left(c_i^* - \overline{c}_{(4ka)}^*\right)/s_{c(4ka)}^*$$

where, for example, $\overline{c}_{(4ka)}^*$ is the mean minimax-rescaled and Box-Cox transformed charcoal value over a pre-defined base period, in this case 10000 to 200 cal yr BP, and $s_{c(4ka)}^*$ is the standard deviation over the same interval. The resulting *z*-scores have a mean of 0.0 and standard deviation of 1.0 (over the base period), which provides an intuitive interpretation of individual values as above or below the long-term mean. When the data are approximately normally distributed, the relative frequency of values of different magnitude can also be inferred. Because the rescaling is linear, the appearance of the standardized time series is identical to the transformed series, and the relationship between transformed and standardized series is identically linear.

Evaluating charcoal records from southern Africa

Individual transformed records and their different resolutions can be visualized using a Hovmüller diagram (SI Fig 1), while the total number of microcharcoal samples over time are shown in SI Fig 2. Composite records were constructed by calculating a mean value across the individual time series at each time interval, while confidence intervals (here 95%) were generated using a bootstrap resampling procedure (main text Fig 2).

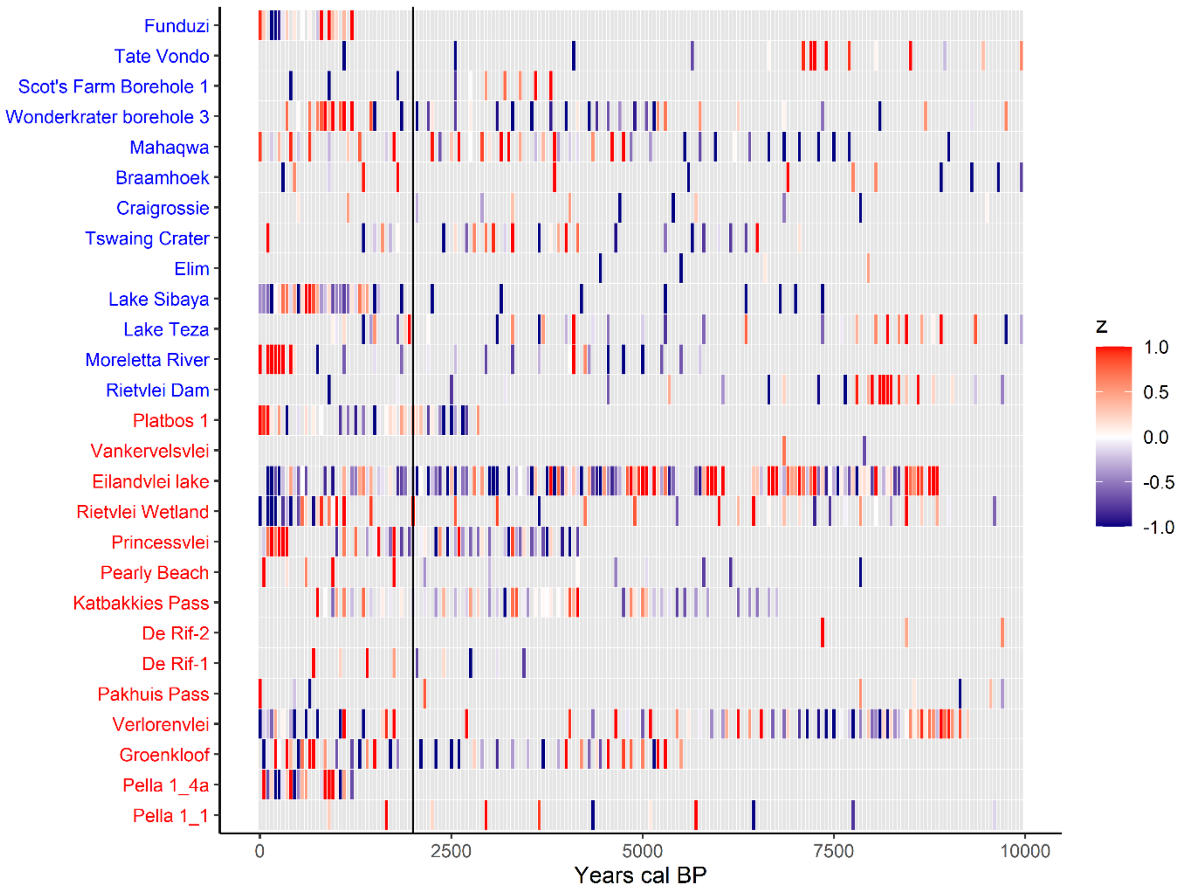
Mapping positive/negative contributions

To generate maps of charcoal influx (Fig 3), dated records from individual transformed records were combined into a single table of site IDs, dates, and latitude/longitude (with 0.1 degree jitter). The table was subset into 2000-year time blocks, and points were plotted semi-transparently, with the size of points indicating *z*-score for individual dated records. Since this plot uses transparency, it would be possible to plot negative points first and positive points second, such that positive points may appear more foregrounded. To alleviate this, points were aggregated and then plotted in alternating fashion (i.e., one positive point, then one negative point, then one positive point, and so on).

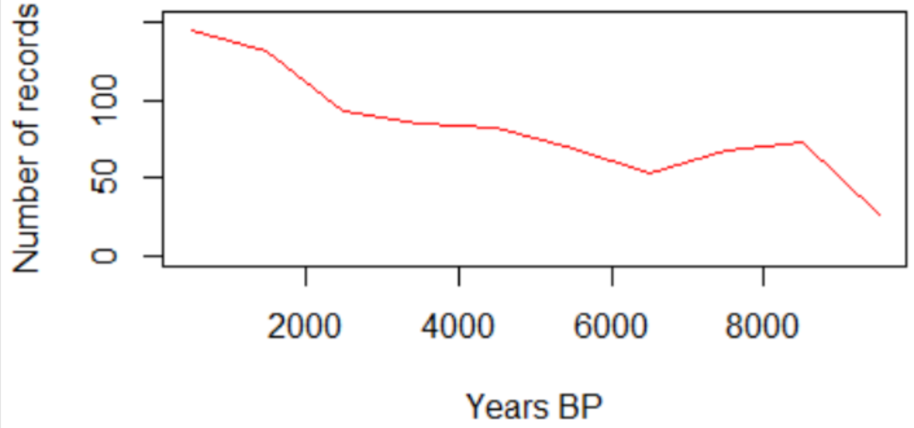
In order to further illustrate the influence of the individual charcoal records on aggregate measures, we mapped the sampling sites contributing to charcoal records and plotted the absolute difference in the number of positive and negative z-score anomaly records in 2000-year intervals regardless of the size of the anomaly (SI Fig 3).

Evaluating the influence of smoothing windows on aggregate microcharcoal records

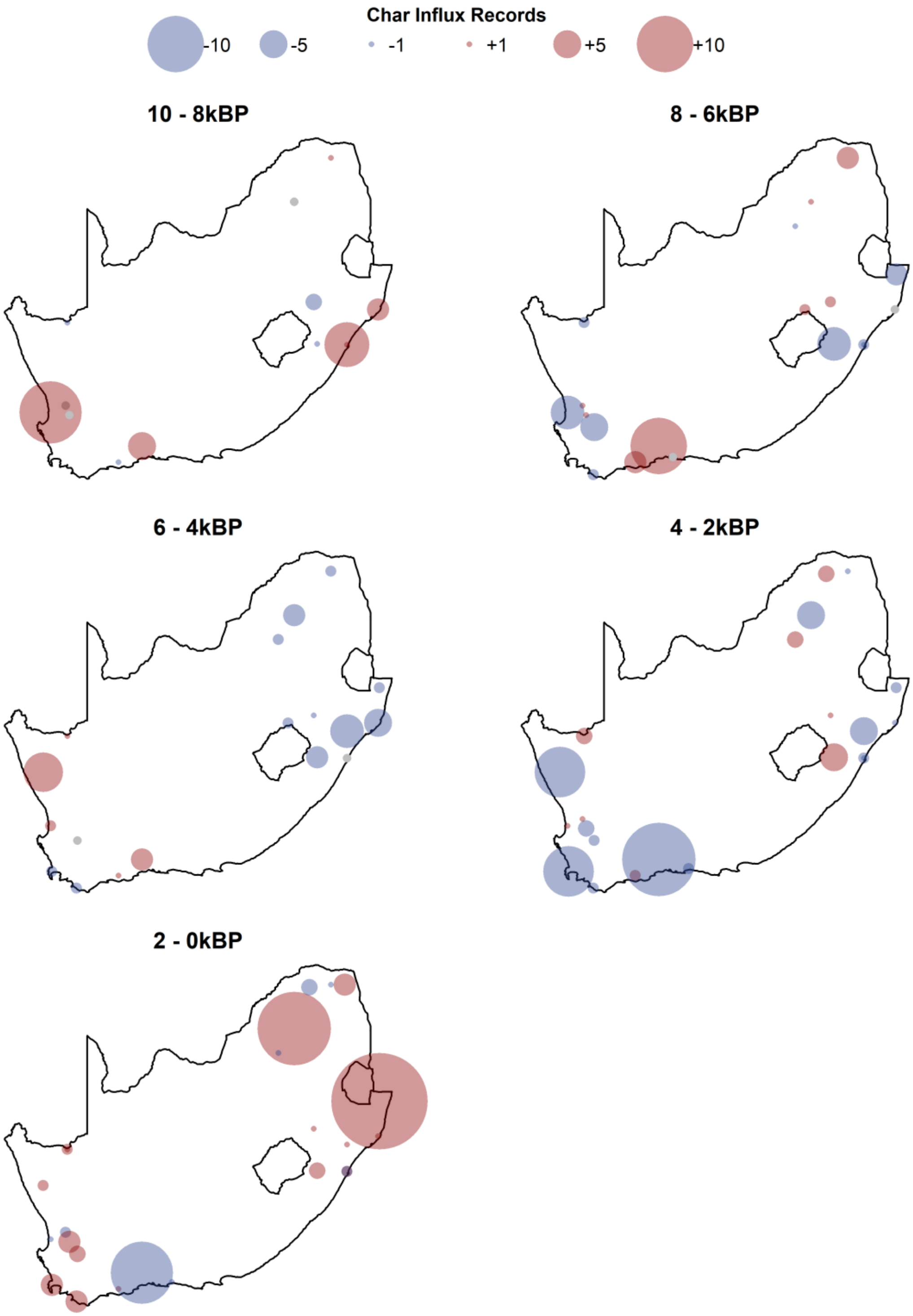
The aggregate microcharcoal assessment uses LOWESS smoothing. Fig 4 plots using both the 250-year halfwidth smoothing window (black) used for the publication graphics, as well as a 125-year halfwidth smoothing window (red) for comparison. For the most part, deviations between are greater for older records, an effect of lower data availability for older records.



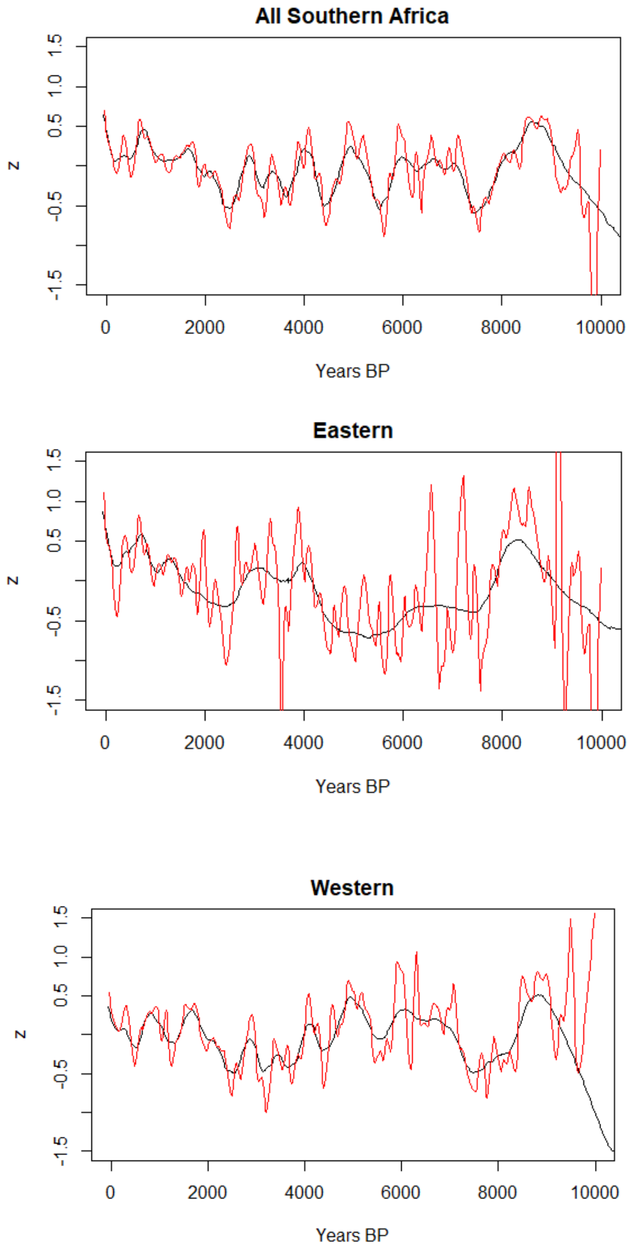
SI Figure 1: Hovmüller diagram showing transformed charcoal influx (z) for South African sampling locations. Scores summed into 50-year bins.



SI Figure 2: Total number of microcharcoal samples per 1000-year bin



SI Figure 3: Maps indicating the absolute difference in the number of positive (red) vs negative (blue) anomalies from transformed charcoal records for 2000-year time intervals. Sites with a net balance of positive and negative events are plotted as a grey dot.



SI Figure 4: Aggregate microcharcoal analyses with 250-year (black) and 125-year (red) smoothing window halfwidths.

Appendix 2: Radiocarbon analysis

Method description

To assess human occupation history, summed probability distributions (SPDs) and site counts were generated using radiocarbon determinations from archaeological surveys and excavations (Fig 4). These methods use the frequency of dated and calibrated cultural materials recovered by archaeologists as a model for the depositional history of these kinds of materials overall (Rick 1987; Williams 2013; Timpson et al. 2014; Weitzel and Codding 2016; Riris and Arroyo-Kalin 2019). Assuming that this record is not substantially or systematically biased by sampling, processing, preservation, visibility, etc. at the scale of observation (but see Williams 2012; Contreras and Meadows 2014; Davies et al. 2016; Becerra-Valdivia et al. 2020), this method provides broad indications of the relative intensity of human activity over time.

Limitations of radiocarbon summed probability approaches have been discussed at length elsewhere (Williams 2012; Torfing 2015a,b; Timpson et al. 2015; Attenbrow and Hiscock 2015; Smith 2016; Williams and Ulm 2016; Hiscock and Attenbrow 2016; Becerra-Valdivia et al. 2020; Ward and Larcombe 2021). To summarize, the principal concerns are:

1. Sampling of the archaeological record is not consistent across time and space. Archaeologists study the record with different research agendas which will influence their approach to sampling. Research designs may target specific layers or features for dating, and greater research interest in particular regions or time periods can inflate numbers of radiocarbon determinations. This can be addressed to some extent by using a binning procedure (SI Fig 5) to account for outlier sites artificially inflating probabilities through repeated dating (Timpson et al. 2014).
2. The radiocarbon calibration process introduces artifacts (steps and plateaus) into an SPD that may exaggerate or deflate probabilities during particular periods of time (Michczyński and Michczyńska 2006). To address this, Williams (2012:584) recommends applying a moving average at 500 year intervals (SI Fig 6), as well as comparing distributions of mean date ages for uncalibrated and calibrated dates to illustrate deviations (SI Fig 7).
3. Preservation and visibility of the archaeological record is not consistent across time and space (Davies et al. 2016). Local preservation and visibility of the archaeological record is largely a product of geomorphic conditions. Most applications of summed radiocarbon data assume that, at a large enough scale, the influences of local geomorphology will be minimized as random noise (Riris and Arroyo-Kalin 2019). However, time-dependent decay is a well-known systematic bias in archaeological studies. To address this, taphonomic correction equations (SI Fig 8; discussed below) have been developed based on securely dated sequences of geological events (e.g.

Surovell et al. 2009; Bluhm and Surovell 2018). Regional processes contributing have not been accounted for here (Ward and Larcombe 2021).

4. Visual comparisons of SPDs can be misleading due to variation in sample sizes (Crema 2022). To support the assertion that differences between eastern and western radiocarbon frequencies are not an artifact of sampling, we used a permutation test (SI Fig 9). In this test, dates from the combined radiocarbon data were selected at random in numbers equivalent to those from the eastern subset, and these were used to generate an SPD. This process is repeated 1000 times to generate an envelope of possible outcomes to show what might be expected from an equivalent sample that is not geographically constrained. This process was then repeated for the western subset. SPDs from the observed data in each subset were then compared to their respective envelopes, illustrating their deviations. In the image below, time periods shaded blue show lower probability than would be expected from a spatially random sample of equivalent size, while those shaded red show higher probability.
5. Archaeologically-derived radiocarbon frequency data are often used as a proxy for population history (e.g. Peros et al. 2010; Williams 2013; Timpson et al. 2014), but it is debatable whether population is the principal force driving changes in radiocarbon frequency (Holdaway et al. 2008; Hiscock and Attenbrow 2016; Freeman et al. 2018). This study avoids this problematic assumption by connecting fluctuation in radiocarbon data to the intensity of human activity, which may be explainable by mechanisms in addition to, or instead of, population change.

Despite these concerns, the corpus of radiocarbon determinations is one of the most broadly comparable datasets available for assessing changes in human activity through time. Unlike other kinds of archaeological data, radiocarbon determinations are enabled by consistent reporting conventions, producing a homogenous collection of data that can be readily aggregated or subset based on research questions. Recognizing these strengths as well as the limitations of these methods, we apply them here to look for broad-scale changes in the deposition of material cultural remains as an indicator of shifts in human activity.

Dataset

Radiocarbon determinations were drawn from the Southern African Radiocarbon Database (*https://c14.arch.ox.ac.uk/sadb*), a collection of data from previously published sources (Loftus et al. 2019). As this study is principally concerned with Holocene changes in southern Africa, the full dataset was subset to include only determinations from the last 10,000 years obtained from sites in Eswatini, Lesotho, and South Africa (*n*=1845). After analyses were performed on this subset, the data were subset further into two subregions of interest: an eastern subset comprised of dates situated within the summer rainfall zone (SRZ; *n*=1148) and a western subset comprised of dates situated within the Greater Cape Floral Region (GCFR; *n*=670). The former is defined as places receiving >66% annual rainfall during summer months (Fig 1A; Tyson

1986); the latter is defined as places featuring Fynbos, Succulent Karoo, or Albany Thicket biomes, or places featuring Forest or Azonal biomes falling within the Winter or Year-Round Rainfall Zones (see main text Fig 1B; Bergh et al. 2014). Finally, both of these, as well as the entire dataset, were subset into determinations from “closed” (sites listed as rock shelters/rock art) and “open” sites.

Analysis

Analyses were undertaken using the *rcarbon* v1.3 software package for the R statistical computing platform (Bevan et al 2019). Code used to conduct the analysis and produce figures from this study is available at https://doi.org/10.5281/zenodo.5130698. Most data cleaning procedures were automated; however, some manual data cleaning was undertaken to remove non-standard characters from numerical data. These operations are detailed in code comments.

Determinations from non-marine sources were calibrated using the ShCal13 southern hemisphere curve (Hogg et al 2013), while those from marine sources were calibrated using the MarineCal13 curve to account for average global marine reservoir effects (Reimer et al. 2013). Local ΔR offsets and errors for marine samples were obtained from the Calib Marine13 database (http://calib.org/marine). Following Riris and Arroyo-Kalin (2019), the nearest reference sources to each site were used. Calibrated dates were not normalized to avoid exaggerated peaks due to calibration curve artifacts.

Summed radiocarbon distributions were generated for all datasets. After sensitivity analysis (SI Fig 5), a 200-year bin size was chosen to minimize the effects of differential sampling. Following Bluhm and Surovell (2018), a taphonomic correction was applied to the SPD for open sites for each dataset:

$$n_t = 21149.57(t + 1788.03)^{-1.26}$$

where n_t is the predicted number of geologic contexts from time t in years before present. The function is built on a large number (n = 4306) of volcanic and other radiometrically dated materials. These were then recombined with the closed sites to generate the final SPD for all southern Africa and the eastern and western subsets.

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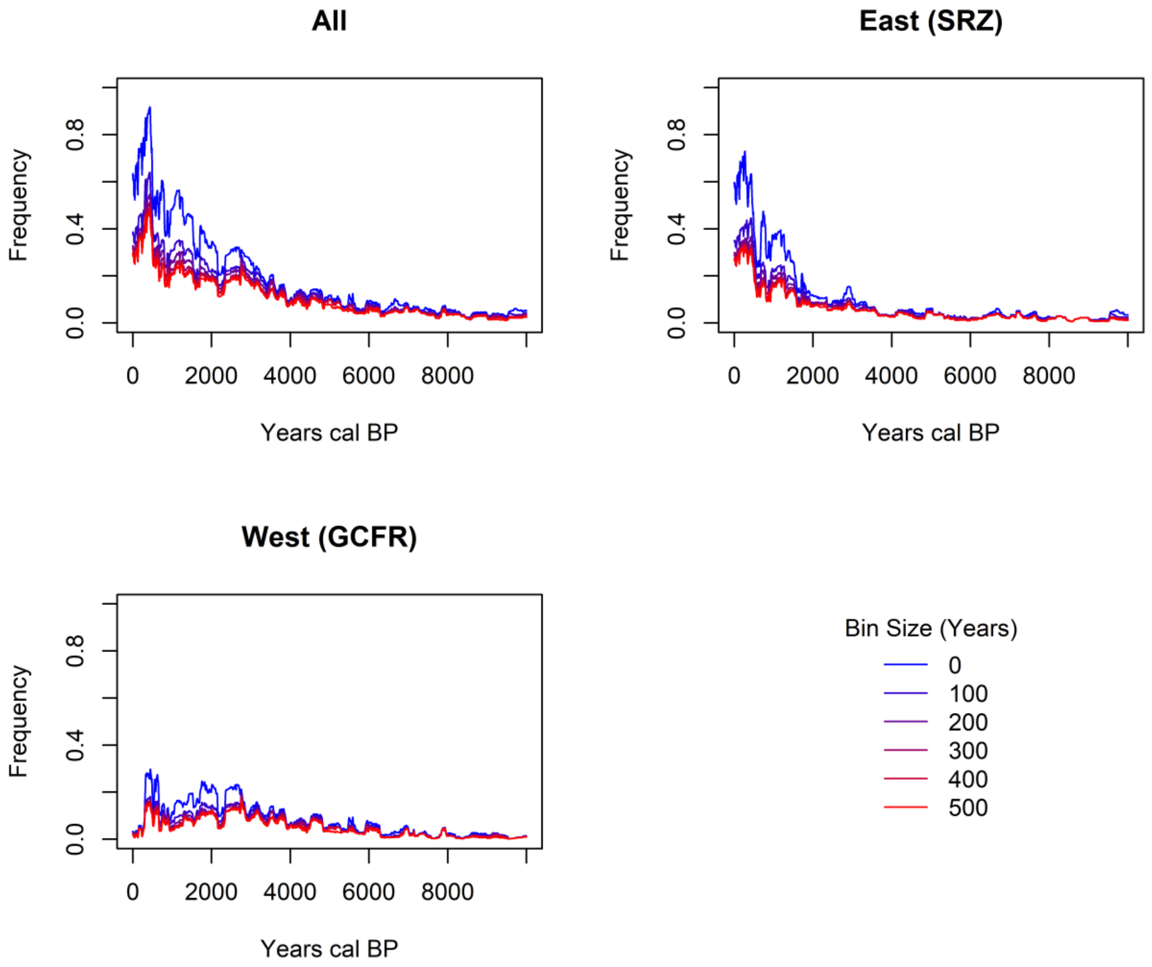
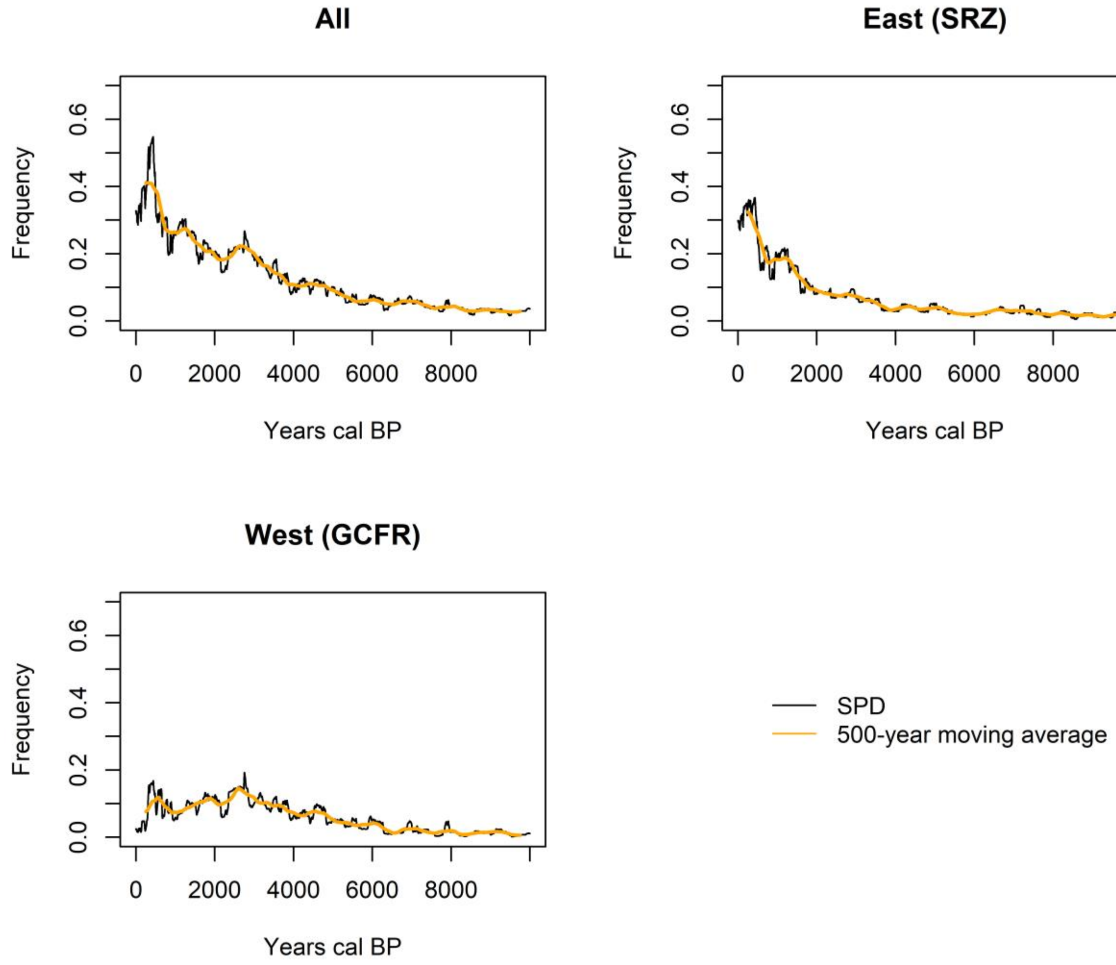
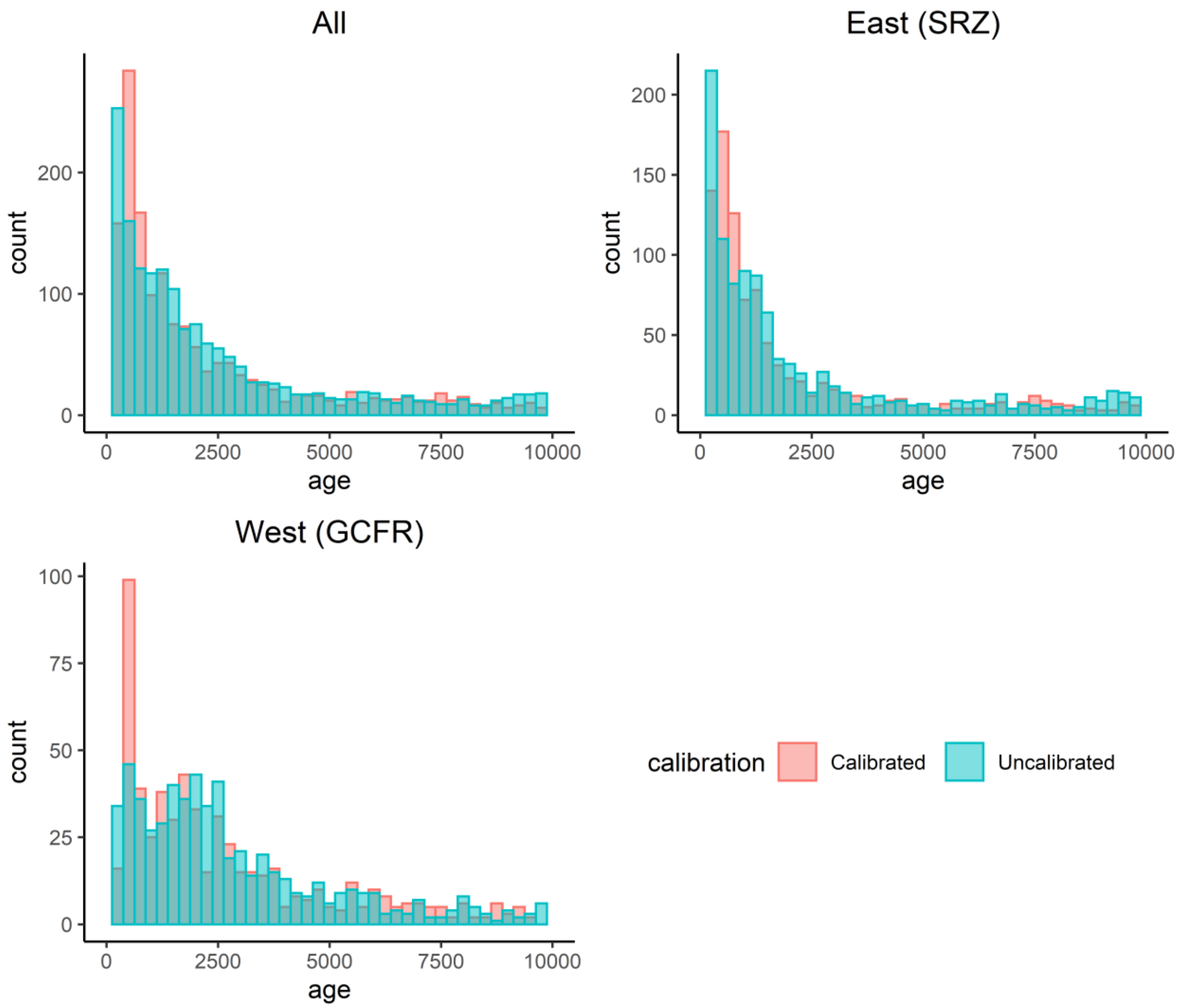


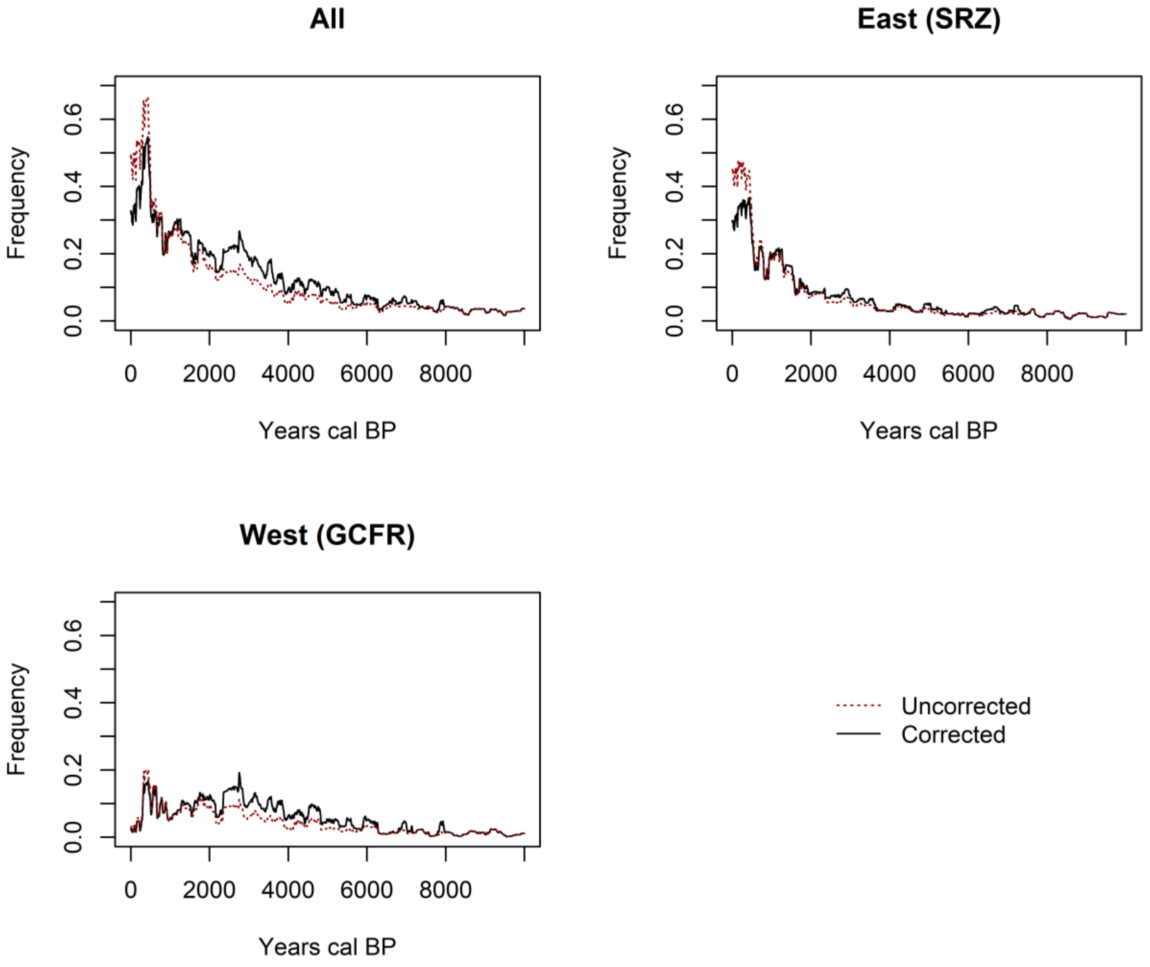
SI Figure 5 Sensitivity analysis for bin sizes used in the generation of SPDs



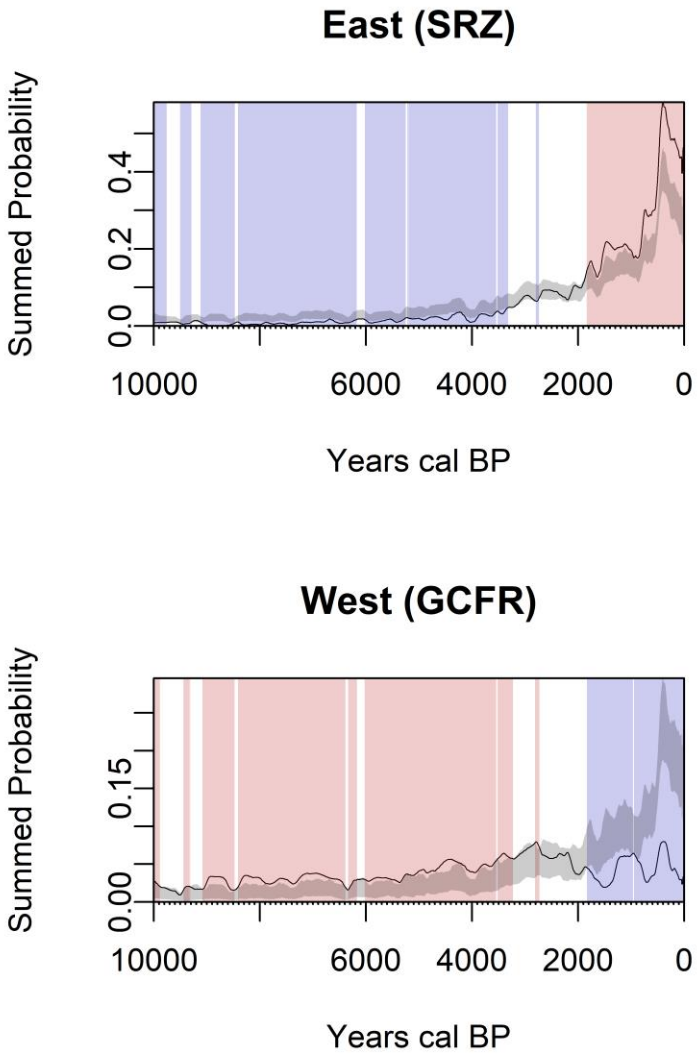
SI Figure 6 Summed Probability Distributions (SPDs) for radiocarbon determinations and 500-year moving average



SI Figure 7 Frequencies of median values of calibrated and uncalibrated radiocarbon dates



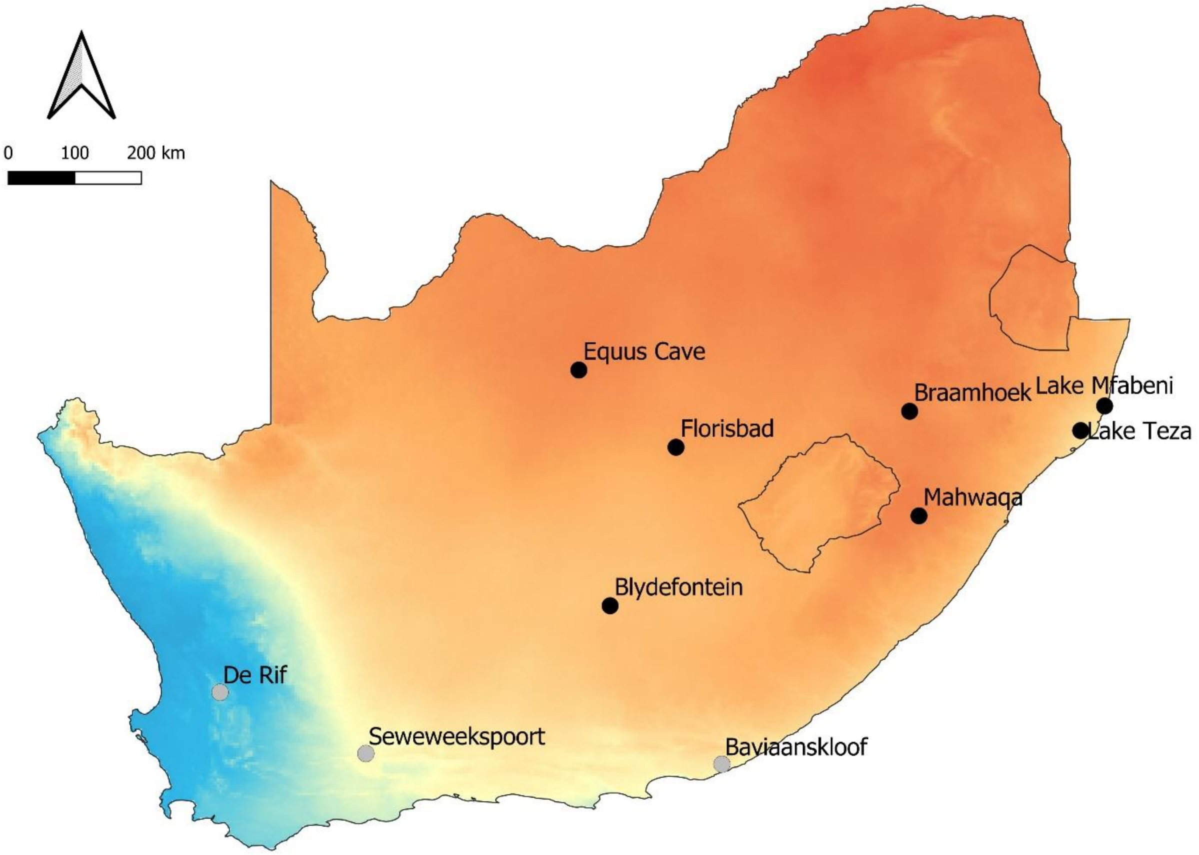
SI Figure 8 Comparison of SPDs using no taphonomic correction (dashed red line) and the taphonomic correction function of Bluhm and Surovell 2018 (solid black line).



SI Figure 9 Permutation test of regional variation in radiocarbon summed probability distributions

Appendix 3: Paleoenvironmental Proxies

In the main text, Figure 4 makes use of previously published paleoenvironmental proxy data from multiple locations in South Africa. The following map indicates the locations of these sampling sites.



SI Figure 10 Map of paleoenvironmental proxies used in Figure 4. Black circles indicate pollen sampling sites contributing to the SRZ southern aridity index (Chevalier and Chase 2016); grey dots are hyrax midden sites used to generate serial δ15N values (Chase et al. 2013; Chase et al., 2011; Chase et al. 2020).

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