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).

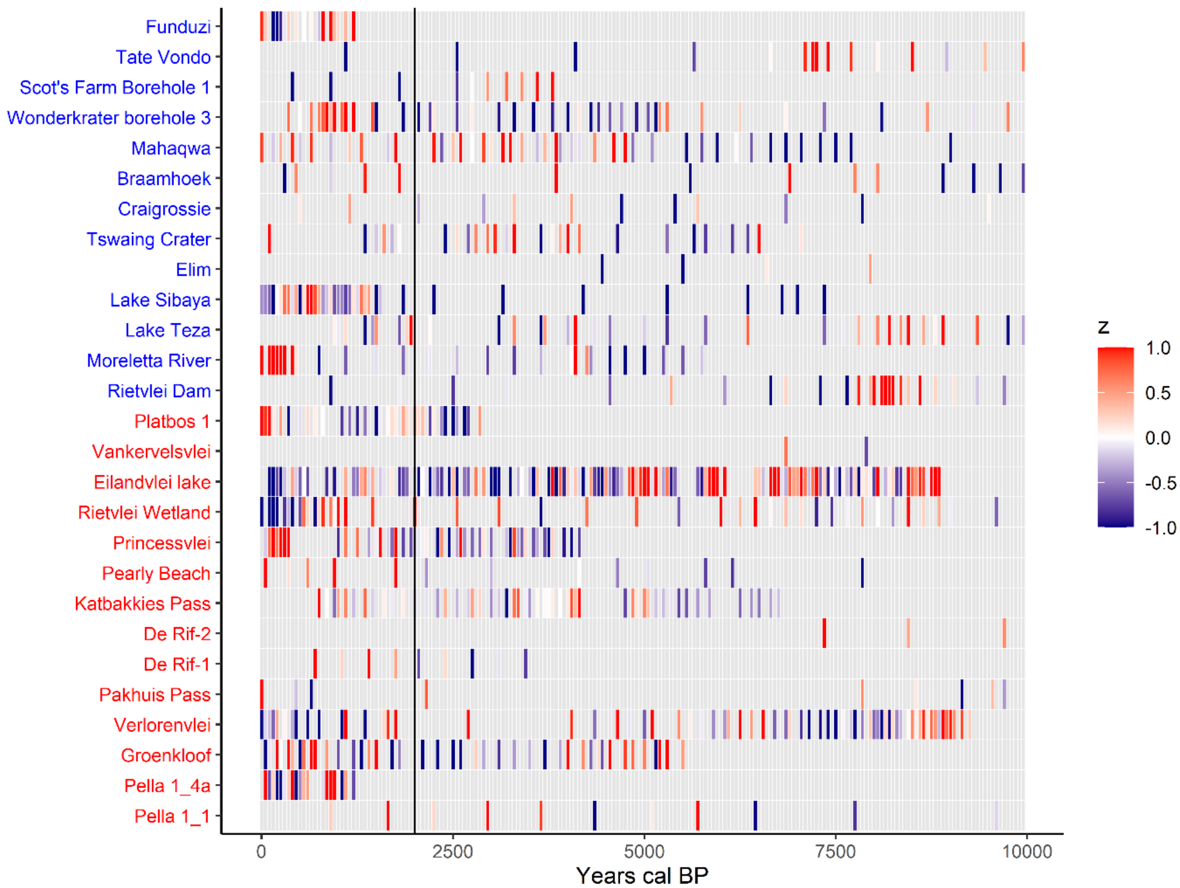
Mapping positive/negative contributions

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).

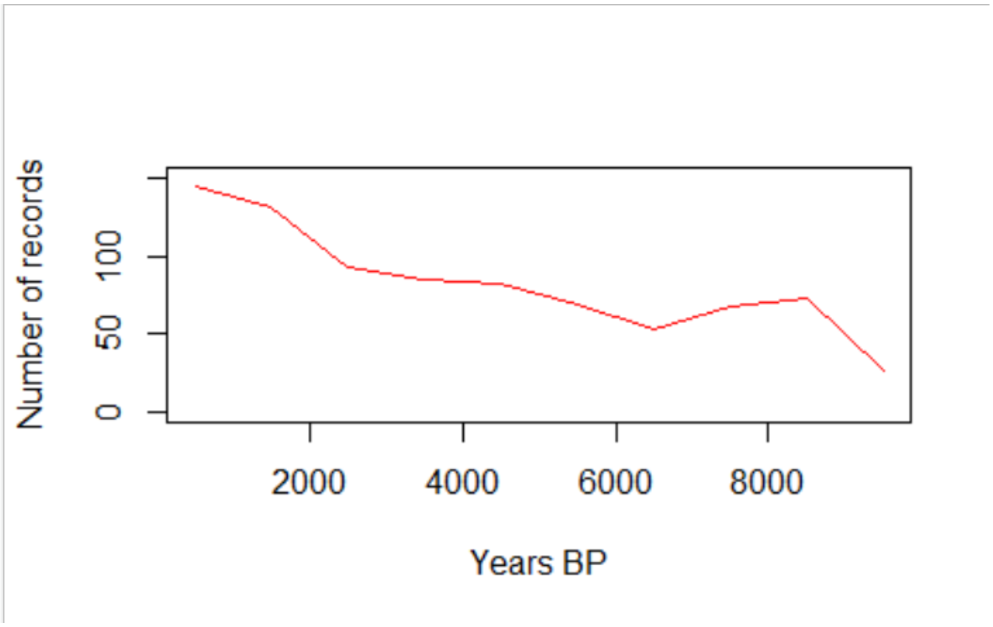
In order to further illustrate the influence of the individual charcoal records on aggregate measures, we mapped the sampling sites contributing to charcoal records and plotted the absolute difference in the number of positive and negative z-score anomaly records in 2000-year intervals regardless of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

Evaluating the influence of smoothing windows on aggregate microcharcoal records

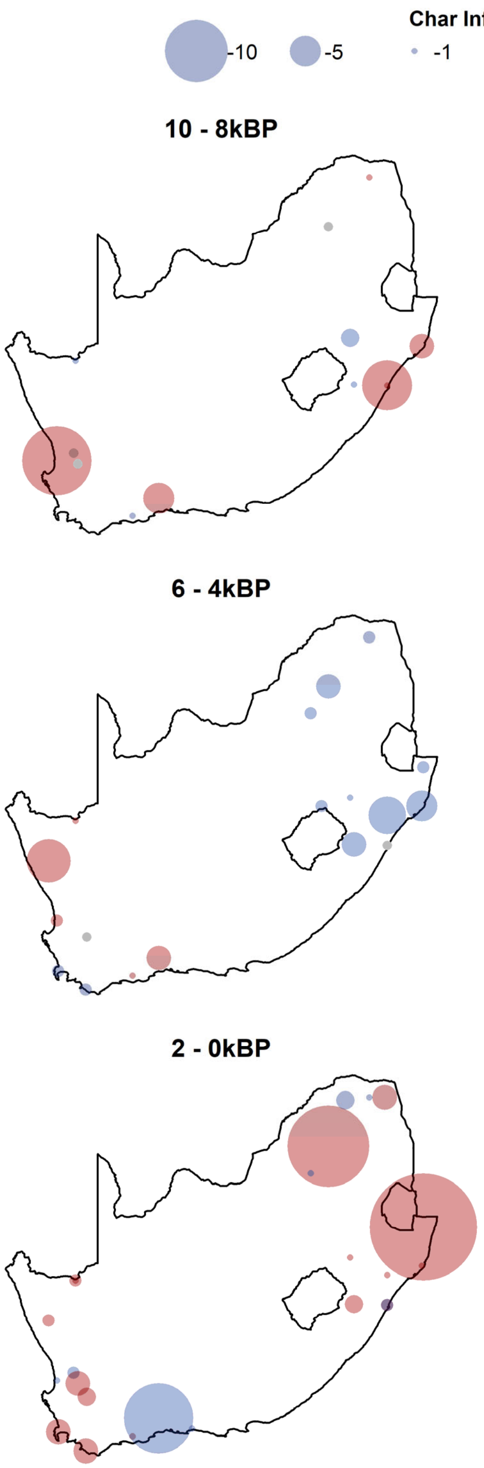
The aggregate microcharcoal assessment uses LOWESS smoothing. Fig 4 plots using both the 250-year halfwidth smoothing window (black) used for the publication graphics, as well as a 125-year halfwidth smoothing window (red) for comparison. For the most part, deviations between are greater for older records,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



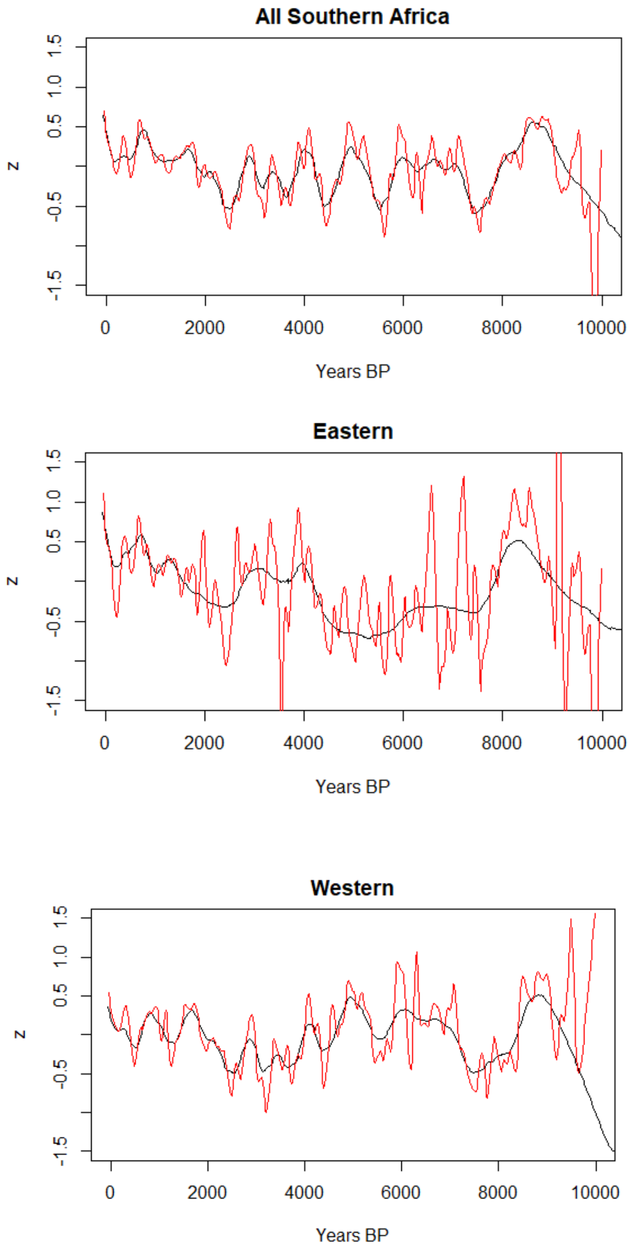
SI Figure 1: Hovmüller diagram showing transformed charcoal influx (z) for South African sampling locations. Scores summed into 50-year bins.



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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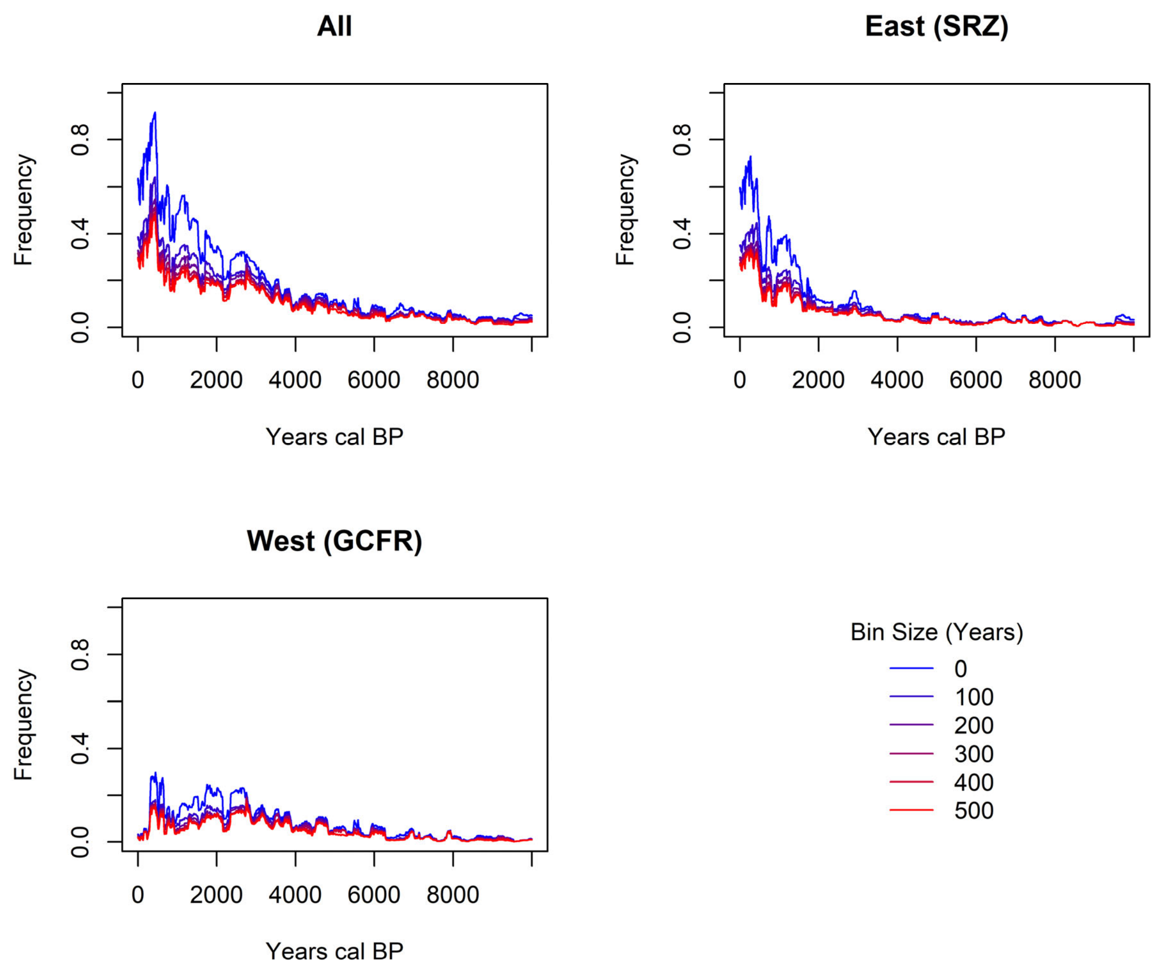
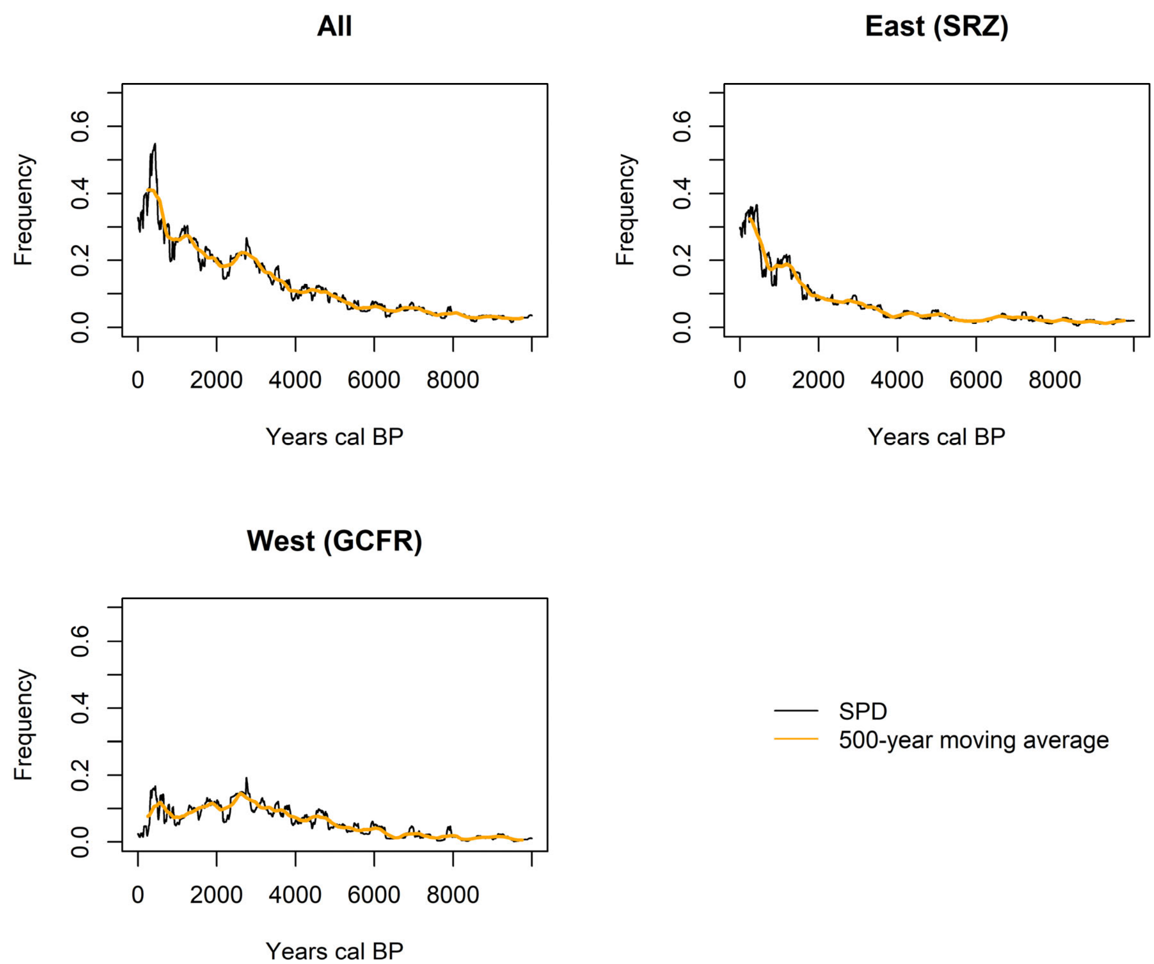
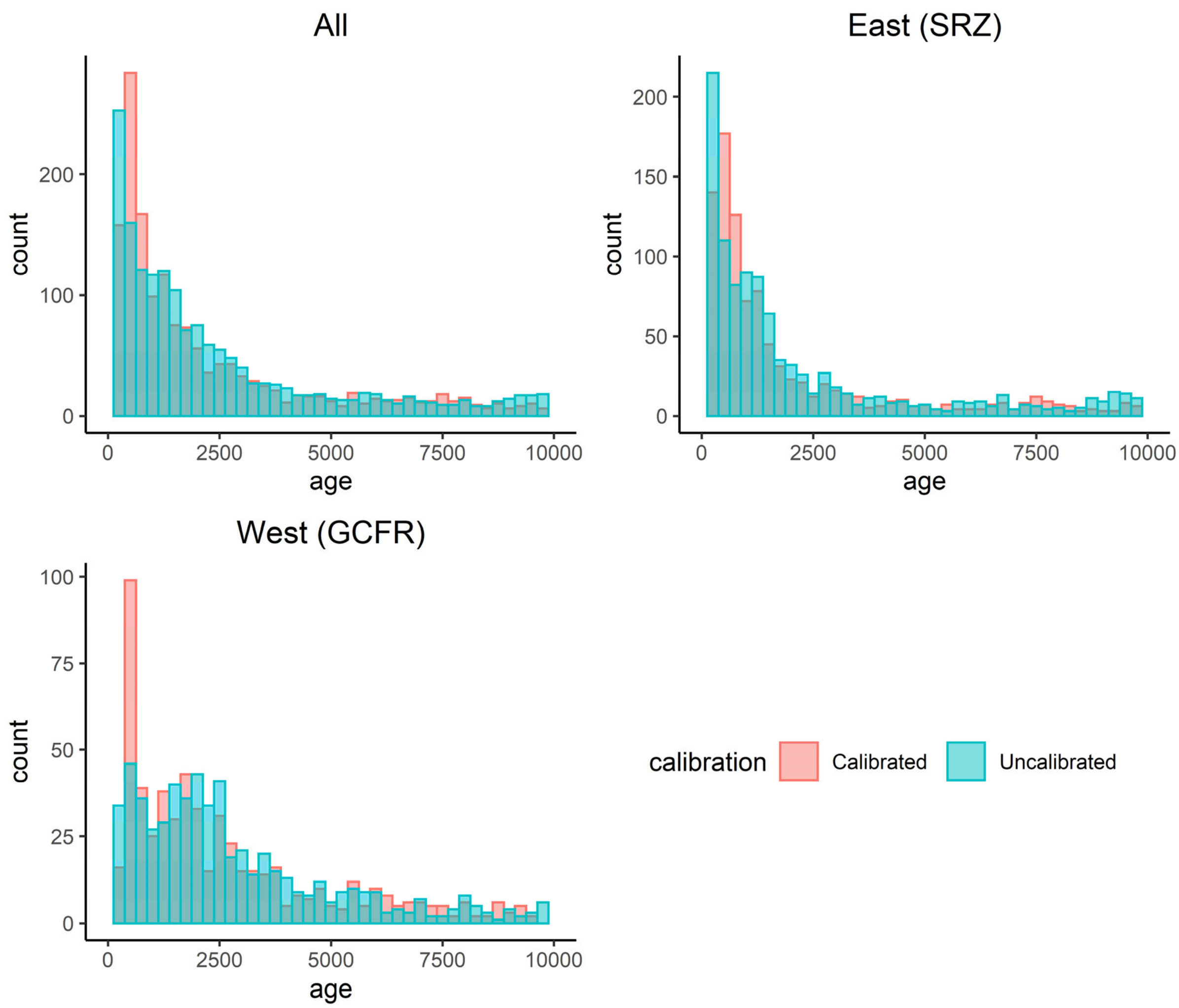


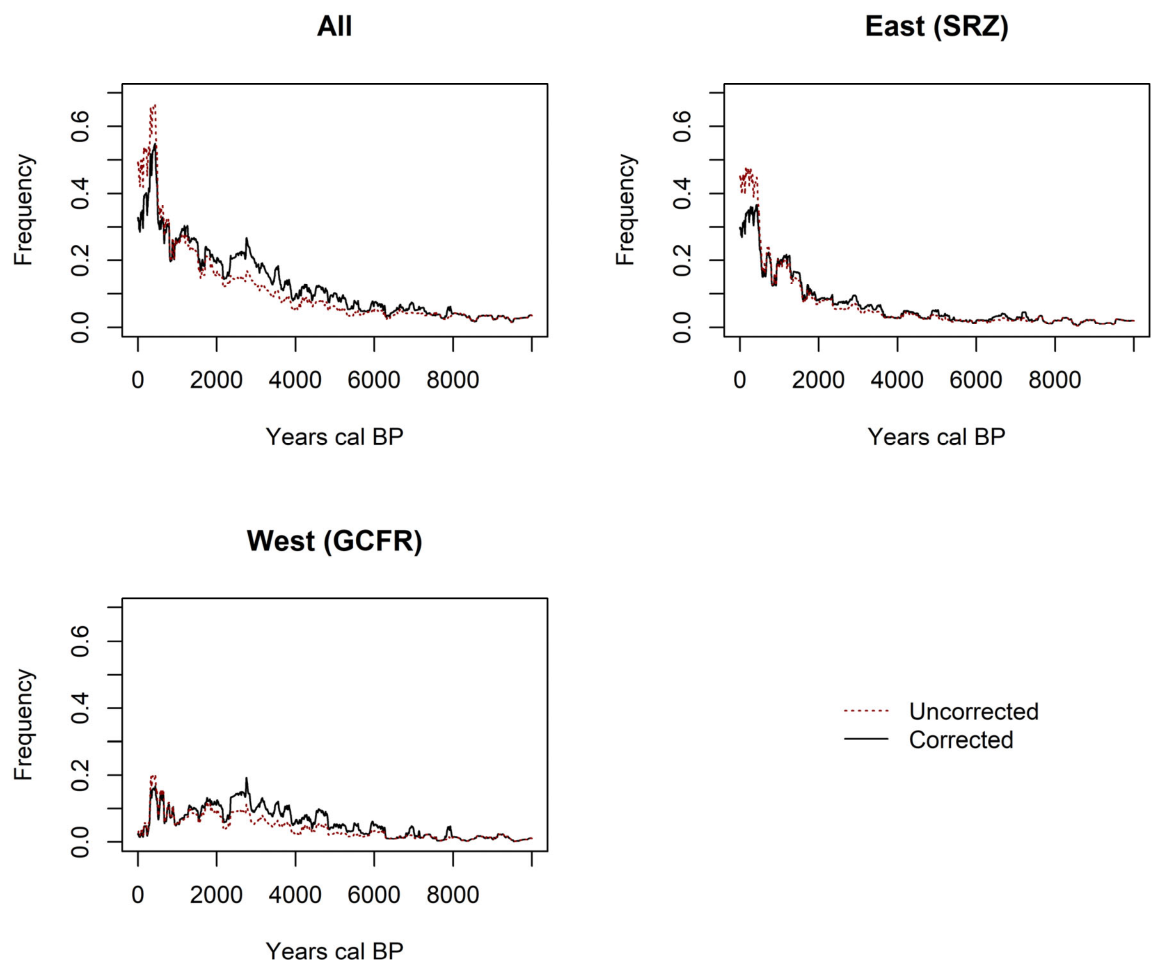
SI Figure 5 Sensitivity analysis for bin sizes used in the generation of SPDs



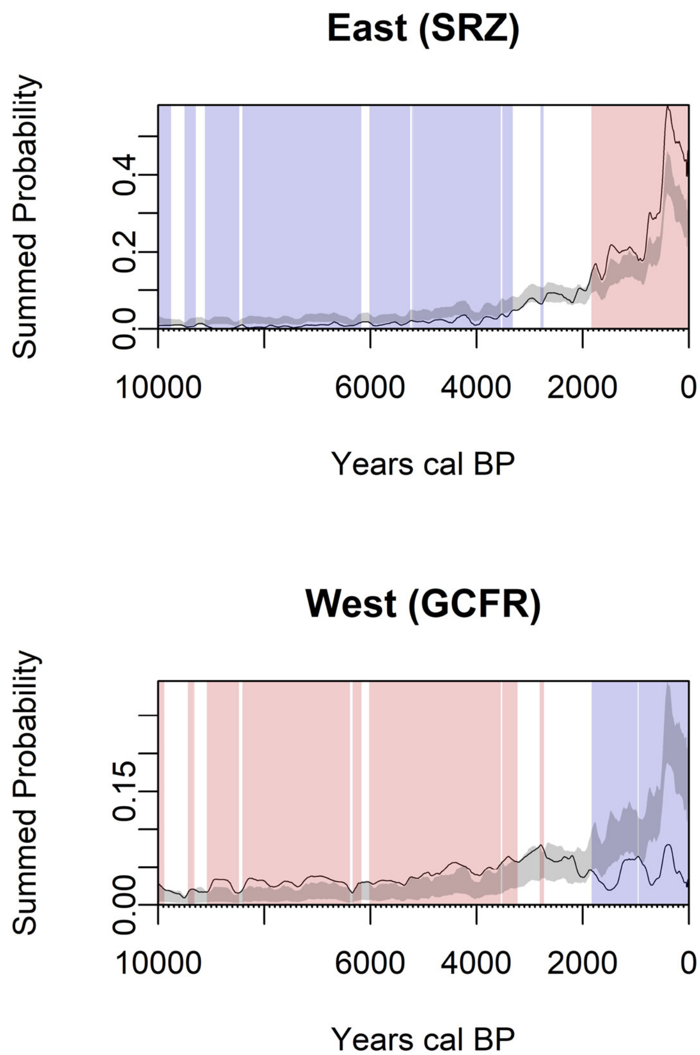
SI Figure 6 Summed Probability Distributions (SPDs) for radiocarbon determinations and 500-year moving average



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



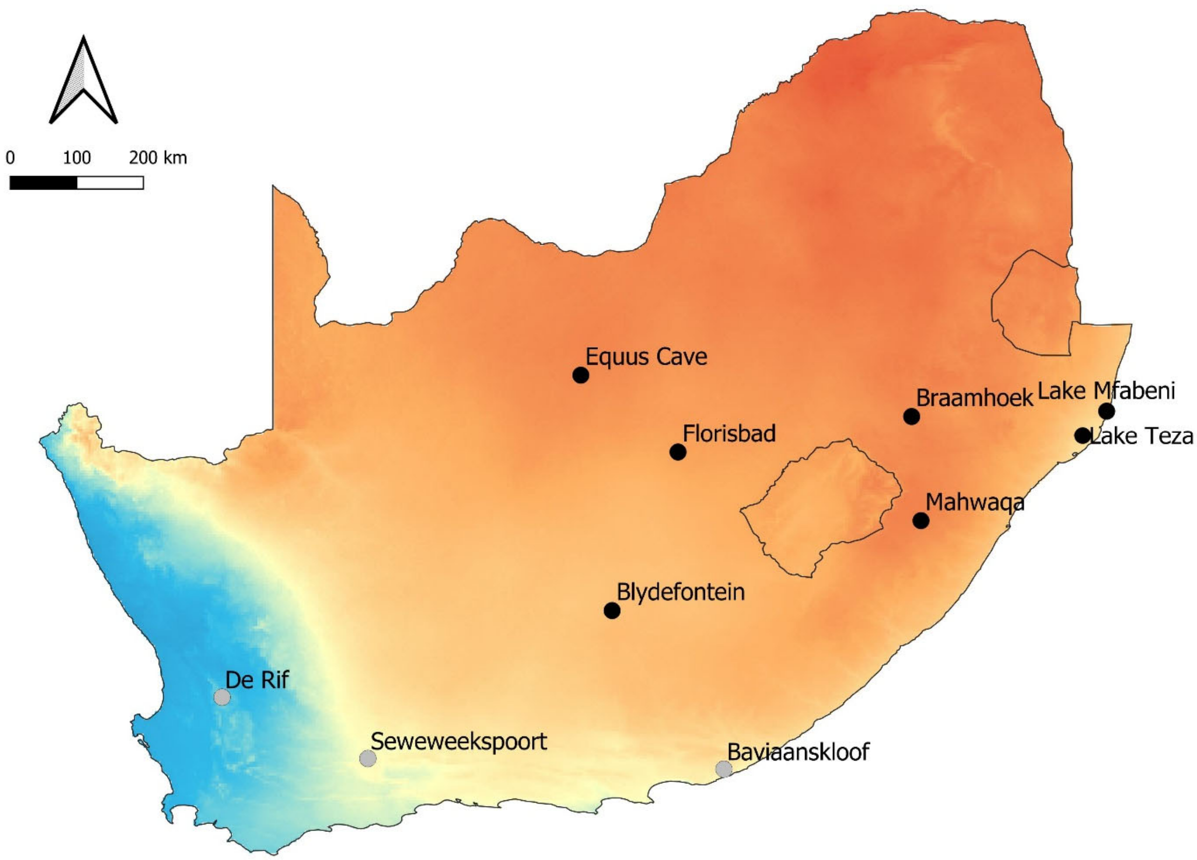
SI Figure 8 Comparison of SPDs using no taphonomic correction (dashed red line) and the taphonomic correction function of Bluhm and Surovell 2018 (solid black line).



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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