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Examining the effects of climate change and human impacts on a high-resolution, late Holocene paleofire record from South Africa's winter rainfall zone

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A R T I C L E I N F O

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A B S T R A C T

Fire is central to the Cape Floristic Region's highly biodiverse and disturbance-adapted Fynbos Biome. However, prehistoric fire regimes, their ecological consequences, and their relationships with large-scale climate drivers and human activities remain poorly understood. Here, we use a high-resolution sedimentary charcoal record from Verlorenvlei, a coastal lake situated on the west coast, to interrogate links between fire, climate, and pastoralism in the Fynbos Biome. Our record has a robust chronology supported by 24 radiocarbon dates and provides a continuous sedimentary sequence spanning the last 4200 years, documenting fire activity before and after the local arrival of pastoralists in the Verlorenvlei area ~1500 cal years BP. Fire at Verlorenvlei over the last 4200 years is variable, with relatively low activity until ~2000 cal years BP, after which variable but generally higher fire activity occurs until the highest period of fire activity from ~1450 to 1800 CE (~500–150 cal years BP). The increase in fire activity ~2000 years ago corresponds with a shift in the diatom assemblage at Verlorenvlei from marine towards brackish and freshwater species, reflecting increased precipitation derived from a strengthening of the southern westerly winds. The peak in fire activity beginning ~1450 CE (~500 cal years BP), near the onset of the Little Ice Age, tracks a second diatom-inferred strengthening of the westerly winds. Other southern hemisphere and Antarctic records further corroborate this increased westerly influence after ~2000 years. Linear regression modeling on the fire record indicates that moisture availability is the primary driver of fire at Verlorenvlei, with little evidence that human populations influenced fire. Our reconstruction suggests that fire activity at Verlorenvlei is limited by moisture availability and that wetter conditions facilitate increased vegetation (i.e., fuel) and intensified fire at this otherwise fuel-limited site. This work has implications for management and conservation decisions in response to future predictions of a warmer and drier climate along South Africa's west coast.

1. Introduction

Quaternary paleoecologists have long focused on disentangling the influence of climate change and anthropogenic impacts on ecosystem structure and fire activity (e.g., Carter et al., 2021; O'Keefe et al., 2023; Roos et al., 2023). However, questions remain regarding the extent to which humans have modified fire beyond "natural" baseline activity, in part due to the difficulties of distinguishing natural from anthropogenic fire. Like many Mediterranean ecosystems, plants in South Africa's Cape Floristic Region (CFR) have evolved alongside fire - experiencing

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frequent burning, with historical fire return intervals ranging between 10 and 15 years (van Wilgen et al., 2010). With an archeological record spanning the past 1 Myr (Braun et al., 2013), the CFR is a compelling location to address climate versus human impacts on fire activity (Braun et al., 2021).

Archeological evidence suggests that the first pastoralist herders arrived in the CFR with sheep around 2000 cal years BP (Klein and Cruz-Uribe, 1989; Marean et al., 2014; Sealy, 2010; Sealy and Yates, 1994). By the time European colonists arrived during the mid-1600s CE, ethnohistoric accounts suggest that both sheep and cattle were regularly being herded and that pastoralists used fire to promote the growth of fresh forage for their livestock (Thom, 1952, 1954). Whether the arrival of pastoralists is associated with altered fire regimes is uncertain – though Davies et al. (2022) suggest that fire in the southwestern Cape may be increasing at the same time. Much research has focused on characterizing paleoenvironmental changes over long-term (centuries-to-millennia) climate and vegetation shifts in the CFR (e.g., Cordova et al., 2019; du Plessis et al., 2020; Manzano et al., 2023; Neumann et al., 2011; Prader et al., 2023; Quick et al., 2015, 2016, 2018, 2022; Valsecchi et al., 2013). These studies reconstruct the region's unique fire histories at multi-decadal to multi-centennial resolution using microcharcoal (and to a lesser extent, macrocharcoal), but detailed studies that offer sufficient resolution to evaluate the drivers of climate versus human controls on fire activity during the late Holocene are lacking. Additionally, the late Holocene contains periods of important hydroclimate changes in the CFR (e.g., Chase et al., 2019; Kirsten et al., 2020; Stager et al., 2012). Here, we employ the first high-resolution paleofire record from the CFR to address the complex interplay of natural factors and human influences over the past 4200 years.

In this paper, we use novel, high-resolution (2–10 year) sedimentary macrocharcoal data from a coastal lake, Verlorenvlei, found in South Africa's winter rainfall zone along the west coast (Fig. 1). Verlorenvlei presents an excellent site as a case-study for this work because of the local, well-constrained records of hydrologic variability (Kirsten et al., 2020; Stager et al., 2012) and its proximity to archeological sites establishing the local timing of pastoralist arrival (Klein and Cruz-Uribe, 1987, 1989, 2016). We explore linkages between climate, fire, and people in this semi-arid, fuel-limited system using charcoal influx, local diatom records (Kirsten et al., 2020; Stager et al., 2012), and both local

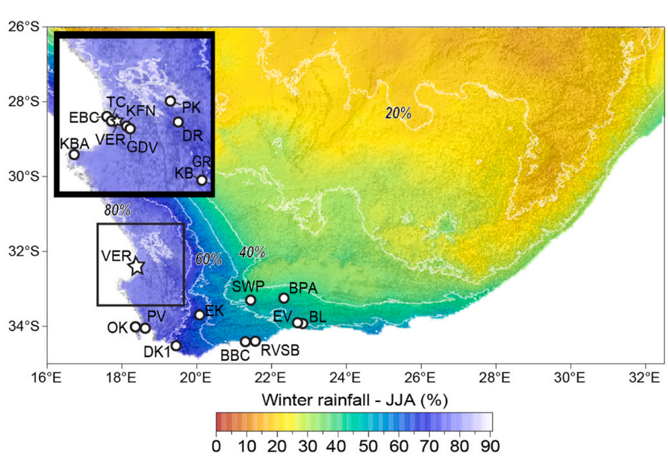

Fig. 1. Map of southern Africa depicting % winter rainfall (June–August). Verlorenvlei (VER; white star) is shown in relation to other paleoecological and paleoenvironmental archives referenced in this text: (KBA – Kasteelberg, EBC – Elands Bay Cave, TC – Tortoise Cave, KFN – Klaarfontein, GDV – Grootdrift, PK – Pakhuis Pass, DR – De Rif; KB – Katbakkies Pass, GR – Groenfontein, PV – Princessvlei, OK – Orange Kloof, DK1 – Die Kelders, EK – Erica Kuil, SWP – Seweweekspoort, BBC – Blombos Cave, RVSB – Rietvlei – Still Bay, BPA – Boomplaas Cave, EV - Eilandvlei, BL – Bo Langvlei). Basemap after Chase et al. (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and regional archeological evidence (Davies et al., 2022; Klein and Cruz-Uribe, 1987, 1989, 2016) to answer: *What are the linkages between fire activity, moisture availability, and pastoralist activity at Verlorenvlei over the past 4200 years?*

Arid and semi-arid environments—like those that characterize the Verlorenvlei area today—have limited fuel moisture and seasonal precipitation, resulting in an increase in burned area as moisture availability increases (Alvarado et al., 2019). Therefore, we expect fire activity at Verlorenvlei to be limited by fuel availability and hypothesize that an increase in moisture will lead to an increase in fire activity (Daniau et al., 2023; Karp et al., 2023). The goal of this work is to contribute towards clarifying the mechanisms controlling fire activity in southernmost Africa, improve our understanding of the impacts and timing of pastoralist burning practices, and benefit future predictions of fire activity under a changing climate.

2. Regional setting

In southern Africa, rainfall seasonality is spatially heterogeneous and driven by major meteorological differences across the sub-continent that result in different proportions of summer versus winter rain. These differences are controlled by high-latitude southern hemisphere climate dynamics (Braun et al., 2019; Chase et al., 2017; Chase and Meadows, 2007). The tropical easterlies carry summertime moisture from the Indian Ocean to the region, and the temperate southern westerly storm track brings winter precipitation as it shifts equatorward seasonally displacing the southern trade winds (Tyson and Preston-Whyte, 2000). The region is also impacted by the transport of warm water along the southern coast in the Agulhas Current and of cold water up the west coast in the Benguela Current. The relationships between these ocean-atmosphere dynamics have resulted in a summer rainfall zone (SRZ) over the eastern and interior parts of South Africa driven by the tropical easterlies, and a winter rainfall zone (WRZ) along the west coast driven by the seasonal expansion of the Antarctic circumpolar vortex and the equatorward shift of the southern westerly winds (Chase and Meadows, 2007; Stager et al., 2012; Tyson, 1986). Between the SRZ and WRZ lies a year-round/aseasonal rainfall zone (YRZ/ARZ), which receives precipitation from both tropical and temperate systems (Fig. 1; Chase and Meadows, 2007; Chase and Quick, 2018).

South Africa's CFR is a product of this unique biogeographic setting wherein the seasonal winter rainfall patterns and ocean-atmosphere dynamics create a temperate, Mediterranean climate encompassing 90,000 km^2 within the Western Cape province. The region is highly biodiverse, with nearly 9000 floral species of which ~70% are endemic (Cowling et al., 2005; Goldblatt and Manning, 2002), making the region a biodiversity hotspot of global significance (Cowling et al., 2003; Myers et al., 2000). The CFR includes three broadly defined vegetation units – fynbos, found growing on sandstone- and quartzite-derived soils with low nutrient content; renosterveld, found on shale- and clay-derived soils with high nutrient content; and strandveld or coastal thicket, located along coastlines (Rebelo et al., 2006). These three units are collectively called the Fynbos Biome. There are also patches of Afrotemperate forest along the southern coast and succulent Karoo along the west coast within otherwise fynbos-dominated localities. Winter rainfall (i.e., a cool growing season) is required for the Fynbos Biome, limiting its spatial extent to the narrow regions reached by the seasonal equatorward shift of the southern westerly winds (Fig. 1).

Fire is important for fynbos biodiversity and reproductive ecology, with many plant species relying on fire at regular intervals (Allsopp et al., 2014; van Wilgen et al., 2010). Ecological case studies have shown that in the absence of fire, fynbos biodiversity has suffered, with some instances of fire-adapted species nearing extinction (van Wilgen, 2009). Despite this recognized importance of fire, the vast majority of what is known about CFR fire history and vegetation response to fire comes from historical ecological studies extending back several decades (Kraaij et al., 2011, 2013, 2018; Kruger, 1984; van Wilgen, 2013). These studies have shown fire return intervals in the CFR typically range between 10 and 15 years, with some variability between southwestern, southern, and eastern fynbos related to differences in rainfall seasonality and human impacts such as infrastructure, commercial pine plantations, and vineyards (Kraaij and van Wilgen, 2014; van Wilgen, 2013). After nearly 300 years of fire suppression policies put in place by European colonists, land managers in the 1970s employed prescribed burning with the goals of ensuring water flow, conserving nature, controlling invasive species, and protecting the economically valuable timber plantations (van Wilgen, 2013).

This study spans notable periods of anthropogenic change over the past 4200 years. The first pastoralist herders in the CFR, the Khoi, arrived in the Cape around 2000 cal years BP and archeological records suggest that they first herded sheep and later, cattle (Klein, 1986; Klein and Cruz-Uribe, 1989; Marean et al., 2014; Sealy, 2010; Sealy and Yates, 1994). Along the west coast, pastoralist herders are documented around 1750 cal years BP at Kasteelberg (Klein and Cruz-Uribe, 1989; Smith, 2021; Smith et al., 1991), and in the vicinity of Verlorenvlei at Tortoise Cave by around 1530 cal years BP and at Elands Bay Cave around 990 cal years BP (Fig. 1; Klein and Cruz-Uribe, 1987; Parkington, 2016b; Robey, 1984). By the time European colonists arrived in the Cape during the mid-1600s CE (~300 cal years BP), both sheep and cattle were regularly being herded. By the mid-1700s CE, European colonists had settled around the Western Cape and had largely suppressed the Khoi way of life (Klein and Cruz-Uribe, 1989).

3. Materials and methods

3.1. Site

Verlorenvlei (32°21″9′S, 18°26″2′E; surface area 10 km^2; maximum depth 5 m) is a coastal, estuarine-lake, river and reed-swamp system located near Elands Bay, approximately 180 km north of Cape Town (Fig. 1; Meadows and Baxter, 1999). The lake extends for 13 km and is, at most, 1.5 km wide, with a catchment over 1890 km^2. It is connected to the Atlantic Ocean by a narrow channel, which is typically blocked by a sandbar at the estuary mouth due to late Holocene sea-level retreat and dune building events about 4000 years ago that reduced the former estuary inlet into the present-day narrow channel (Whitfield et al., 2017). Today, much of the lake is dry or extremely shallow due to water redirection for agriculture and lack of rainfall. The lake also experiences high evaporative and seasonal losses (Meadows et al., 1996). The setting is ecotonal between karroid and fynbos vegetation, surrounded by Lowland Fynbos, Dry Mountain Fynbos, and wetland vegetation (Meadows et al., 1996).

3.2. Core extraction and chronology

During a field campaign in 2014, one gravity core (VER14-5 (1.02 m)), and two parallel piston cores (VER14-7 (16 m) and VER 14-9 (14 m)) were extracted using a UWITEC system (Haberzettl et al., 2016; Kirsten et al., 2020). The cores were transported to the Friedrich Schiller University, Jena, Germany, and were split and documented following standard procedures. Magnetic susceptibility and optical marker layers were used to correlate the overlapping cores, and a composite record of 15.25 m ('VER14') was established. Here, we focus on the charcoal record from the top 4.3 m of the VER14 composite to encompass the two millennia before and after the regional arrival of pastoralist herders (Fig. 2).

Magnetic susceptibility and particle size distribution were used to identify event-related deposits (ERDs), which likely occurred rapidly over the course of hours to days and were excluded from the age-model (following the protocol outlined in Kirsten et al. (2020)). ERDs were not included in the charcoal record. The chronology for the Verlorenvlei record was adapted from Kirsten et al. (2020) and recalibrated using the 2020 marine and southern hemisphere calibration curves (Marine20 and SHCal20) (Heaton et al., 2020; Hogg et al., 2020) in OxCal version 4.4 (Bronk Ramsey, 2009).

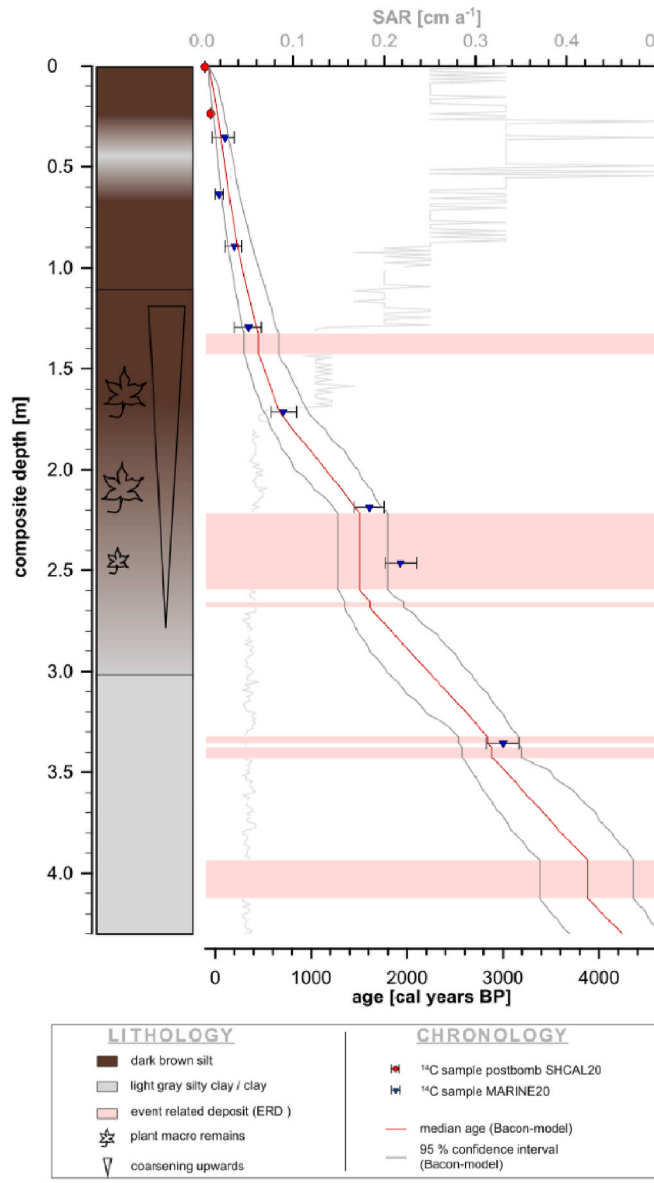

Fig. 2. The lithology, chronology, and sediment accumulation rate (SAR) of the top 4.3 m of the VER14 composite core. Red lines indicate event-related deposits (ERDs), which are excluded from the record as they likely occurred over the course of hours to days. Refer to Kirsten et al. (2020) for a complete list of radiocarbon ages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

To place the VER14 core within a broader archeological context, we used the African Radiocarbon Database (Loftus et al., 2019) to source radiocarbon ages and their associated uncertainties from Kasteelberg (Smith et al., 1991; Klein and Cruz-Uribe, 1989), Tortoise Cave (Robey, 1984; Klein and Cruz-Uribe, 1987), and Elands Bay Cave (Klein and Cruz-Uribe, 1987, 2016; Parkington, 2016b), and calibrated them using the SHCal20 calibration curve (Hogg et al., 2020) in OxCal version 4.4 (Bronk Ramsey, 2009).

3.3. Charcoal analyses

Approximately the uppermost 4.3 m of the VER14 sedimentary sequence covering the past 4200 years were sub-sampled at 0.5 cm resolution to produce the first high-resolution record of fire activity from

Verlorenvlei, with individual samples representing 2–10 years. Samples averaged 1.5 g and were placed in 15 ml test tubes with 3 ml of sodium hexametaphosphate to assist in the deflocculation of clay-rich sediments. Samples were then soaked for 24–72 h. Volumetric displacement was measured, and samples were wet sieved through a 125 μm sieve. Residue was washed into gridded Petri dishes for counting under a Zeiss Stereomicroscope at 36x magnification. In total, 870 charcoal samples were counted.

Raw charcoal data was converted into influx (particles/cm^{-2}/yr^{-1}) using CharAnalysis in MATLAB (Higuera et al., 2009). The median resolution of 8 years was used to smooth the full record. A smoothing window of 150 years (18.75 samples per window) resulted in a signal-to-noise ratio of 2.8 (Kelly et al., 2017).

To better visualize changes in charcoal influx over time, raw charcoal influx was transformed in R (R Core Team, 2023) using a standardized Box-Cox power transformation by (1) rescaling the values using a minimax transformation; (2) homogenizing the variance using the Box-Cox transformation over the interval of 2000 to 200 cal years BP; and (3) rescaling the values again to z-scores (following Power et al., 2008). The choice of base period from 2000 to 200 years represents a range of variable charcoal influx values and excludes the onset of industrial activity. Alternate options for Box-Cox base periods are visualized in Appendix A (Fig. A1).

We use regime shift analysis to identify abrupt changes in the charcoal record and facilitate our discussion. Regime shifts in raw charcoal influx data were detected using Sequential Regime Shift Detection version 3.2 in Excel (Rodionov, 2004). Probability was set to 0.05 with a cutoff length of 275 and a Huber parameter (a measure of robustness to outliers) at 6.

3.4. Linear regression modeling

A linear regression model was used to quantify the relative importance of several possible independent variables on fire activity. These include moisture availability (Kirsten et al., 2020), human population density (Davies et al., 2022), and the interaction between them. Moisture availability was inferred using detrended correspondence analysis (DCA) Axis 1 values of the Verlorenvlei diatom record (following Kirsten et al., 2020), which documents a shift in diatom composition from marine-dominated towards brackish- and freshwater-dominated diatoms around 2000 cal years BP. Human population density is inferred from summed probability density (SPD) analysis of archeological radiocarbon dates from the CFR (Davies et al., 2022). SPDs were corrected for taphonomic bias, which favors younger archeological records, following equations derived by Surovell et al. (2009) and Bluhm and Surovell (2019), but see Davies et al. (2022) for further details. The model incorporated Box-Cox power transformed charcoal influx, the DCA Axis 1 data from Kirsten et al. (2020), and z-score transformed, taphonomically corrected SPD data from Davies et al. (2022). Model AIC scores were used to select the best model and are presented in Table 1 alongside the selected model results. Models were performed in R (R Core Team, 2023). Model output summary statistics are provided in Appendix B.

Table 1
Evaluation of linear regression models to predict fire activity as a function of moisture and people in the CFR over the past 4200 years. The model dependent variable is charcoal influx Box-Cox transformed over the 200–2000 cal years BP base period. The model in bold indicates the best model as determined by AIC score.

Model	AIC	ΔAIC	r^2 adjusted	*p*
Moisture Only	**1404.36**	**3.15**	**0.69**	**<0.001**
Moisture + People	1405.48	4.27	0.69	<0.001
People Only	1970.92	569.7	0.02	0.0015

4. Results

Over the past 4200 years, fire activity at Verlorenvlei has been variable, but generally shows an increasing trend over time (Fig. 3). Embedded within this generally increasing trend are periods of lower, more variable, and higher fire activity. Regime detection identified three zones, hereafter referred to as VER 1 (∼4260–2200 cal years BP), VER 2 (∼2220–680 cal years BP), and VER 3 (∼680 to −64 cal years BP). VER 1 spans the pre-pastoral period; VER 2 encompasses the arrival of pastoralists; and VER 3 includes the arrival of European colonists in the mid-1600s CE (∼300 cal years BP) and the Little Ice Age from 1400 to 1700 CE (550–250 cal years BP; (Mann et al., 2009).

4.1. VER 1 (∼4260–2200 cal years BP)

Overall fire activity is low during this period, but highly variable (Fig. 3A). The median resolution during this period is 10 years per 0.5 cm sample. Low fire activity during VER 1 corresponds with a primarily marine diatom community composition (Fig. 4D; Kirsten et al., 2020), generally low fire activity across the west coast, and low but increasing human population density, which peaks during VER 1 ∼2500 cal years BP (Fig. 4B-E; Davies et al., 2022). There are two brief periods of increased fire activity at ∼2900 cal years BP and a slight increase at ∼2650 cal years BP (Fig. 3A), which both fall within a period of slightly elevated fire activity across the west coast (Davies et al., 2022), suggesting that these episodes of increased burning were also experienced across the region (Fig. 4C).

4.2. VER 2 (∼2200–680 cal years BP)

Fire activity is higher in VER 2 than in VER 1, reflecting a trend of generally increasing fire relative to the previous period (Fig. 3A). The median resolution during this period is 9 years per 0.5 cm sample. VER 2 spans a notable shift in diatom community assemblage from predominately marine to predominately brackish and freshwater diatoms ∼2000 cal years BP (Fig. 4D; Kirsten et al., 2020). Fire similarly shifts

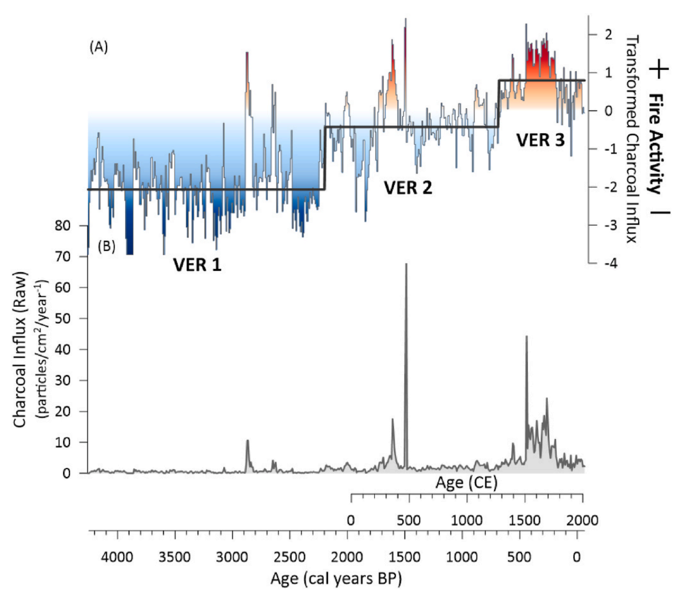

Fig. 3. Verlorenvlei fire history reconstruction. A) Box-Cox transformed charcoal influx and B) raw charcoal influx (particles/cm^{-2}/yr^{-1}). Data are shaded in blues to represent relatively lower fire activity, and reds to represent relatively higher fire activity. The black lines across Panel A are regimes detected using Sequential Regime Shift Detection version 3.2 in Excel (Rodionov, 2004). The regimes zones are: VER 1 (∼4260–2200 cal years BP), VER 2 (∼2200–680 cal years BP), and VER 3 (∼680 to −64 cal years BP).

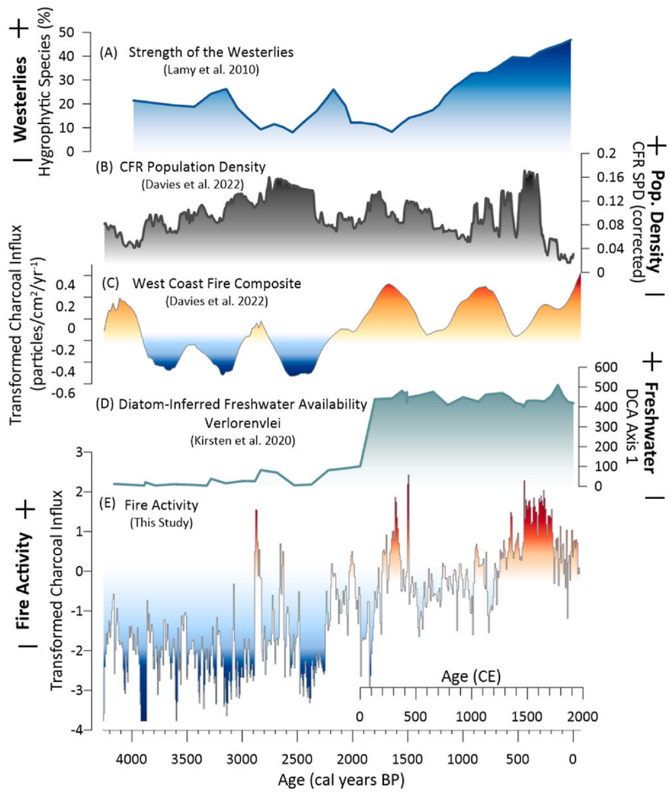

Fig. 4. Comparison of the Verlorenvlei charcoal record to regional and hemispheric archives. A) Hygrophytic pollen taxa from Chile's Gran Campo Nevado mountains, interpreted to track increased moisture availability linked to a strengthening of the southern westerly winds (Lamy et al., 2010). B) CFR taphonomically corrected summed probability density data (Davies et al., 2022) as a metric for human population density on the landscape. C) CFR fire composite (termed "West Coast" in Davies et al. (2022)) using Box-Cox transformed charcoal influx data from regional records (see sources within Davies et al. (2022) for individual archives). D) DCA Axis 1 scores on diatom community assemblage data from VER14 (Kirsten et al., 2020), reflecting a strengthening in the southern westerly winds and increased precipitation at Verlorenvlei ~2000 cal years BP. E) Box-Cox transformed charcoal influx data from VER 14 (this study).

from lower activity early in VER 2 (~2200–2000 cal years BP) towards the highest fire activity between ~1700 and 1500 cal years BP, with the largest peak at ~1500 cal years BP (Fig. 3A). After this peak, fire activity again drops to levels seen near the start of VER 2 and remains around this level until the start of VER 3 (Fig. 3A). Similarly, fire activity across the west coast shifts towards variable but higher activity after 2000 years (Fig. 4C), while human population density is variable but generally decreasing over VER 2 (Fig. 4B). This decrease in human populations at a time of increasing fire is contrary to expectations that fewer people on the landscape will result in fewer fires.

4.3. VER 3 (~680 to −64 cal years BP; 1270–2014 CE)

Fire activity is the highest during VER 3 and shows notably less variability than in previous zones (Fig. 3A). This period includes both the arrival of European colonists into the CFR ~1650 CE (~300 cal years BP) as well as the Little Ice Age (LIA; 1400–1700 CE; 550–250 cal years BP). The median resolution for this period is 2 years per 0.5 cm sample. Results suggest that fire activity at Verlorenvlei is already high relative to the earlier parts of the record and throughout the LIA, especially from ~1450–1800 CE (Fig. 3A; 500–150 cal years BP). Fire activity begins to increase ~1270 CE (~680 cal years BP), and especially after ~1450 CE (~500 cal years BP), revealing that fire activity was already high before the arrival of Europeans in the mid-1600s CE. Human population density is at its highest between ~1500 and 1800 CE (~450–150 cal years BP), corresponding with the period of high fire activity and beginning before European arrival in the mid-1600s CE (Fig. 4B and E). This peak in the human population is on par with the estimated density at ~2500 cal years BP, when fire activity was generally lower and more variable, suggesting that the association between fire activity and corrected SPD data may be spurious. From the mid-to late-1700s CE (~200 cal years BP) towards the present, fire activity at Verlorenvlei is lower than during much of the LIA but remains higher than over most of the past 4260 years (Fig. 3A).

4.4. Linear regression model

AIC scores from various models are presented in Table 1. The best model (lowest AIC score; bolded) includes moisture availability only (Kirsten et al., 2020) and explains 69% of the variability in charcoal influx. The model is highly significant ($p < 0.001$). The second strongest model includes both moisture availability and people ($p < 0.001$), but only moisture availability is highly significant ($t = 31.960$, $p < 0.001$), while human population density is not significant ($t = -0.953$, $p = 0.341$; Table 1). The model including only people is significant but explains only 2% of the variability in charcoal influx ($p = 0.0015$; Table 1). Moreover, the correlation between fire activity and human population densities is negative, counter to our expectations that more people on the landscape would result in greater fire. Model output summary statistics are provided in Appendix B.

5. Discussion

5.1. VER 1 (~4260–2200 cal years BP)

The low fire activity at Verlorenvlei during VER 1 corresponds with drier conditions, reduced bioproductivity, low biodiversity, and a marine regression (Carr et al., 2015; Kirsten et al., 2020; Meadows and Baxter, 2001; Miller et al., 1993). Low diatom concentrations and TOC/TN ratios until ~2400 cal years BP further corroborate the reduced bioproductivity associated with low sea levels and a low energy, shallow system until ~2000 cal years BP (Kirsten et al., 2020). Despite low overall concentrations, the diatom assemblage is dominated by marine diatoms, suggesting reduced freshwater inputs and higher salinity. Salinity is primarily impacted by changes in sea level and precipitation at Verlorenvlei, where sea levels retreated from their peak of 2.8 m higher than today ~4200–4000 years ago towards levels within 1 m of present (Baxter and Meadows, 1999; Compton, 2001, 2006; Ramsay, 1995; Whitfield et al., 2017).

Other local and regional proxies have likewise revealed dry conditions and reduced marine influence during this period. At Elands Bay Cave, mollusk records indicate that sea levels dropped from as much as 2 m higher than today towards present-day levels between 3500 and 2800 cal years BP (Jerardino, 1997). Pollen and sediment accumulation records from Grootdrift and Klaarfontein suggest periodic desiccation and limited freshwater availability after 4300 cal years BP as evidenced by a limited terrestrial pollen signal, especially among fynbos and scrub-forest elements, and a dominance of Poaceae, Asteraceae, and Chenopodiaceae, which reflect xeric conditions and limited freshwater availability (Meadows and Baxter, 2001; Meadows et al., 1996). Other Western Cape sites (Fig. 1) have also documented hydroclimatic shifts in the late Holocene. At De Rif, 64 km from Verlorenvlei in the Cederberg Mountains, pollen and microcharcoal records from hyrax middens suggest drier and more seasonal conditions ~3000 cal years BP (Valsecchi et al., 2013). Princessvlei, 13 km southwest of Cape Town, similarly reflects a drier fynbos community represented by Asteraceae, *Crassula*, and Aizoaceae from 4150 to 3400 cal years BP, but also documents a transition towards swampy conditions ~3400 cal years BP, possibly related to a high groundwater table (Neumann et al., 2011). At Pakhuis

Pass (Chase et al., 2019) and Katbakkies Pass (Chase et al., 2015) hydroclimate shifts over the Holocene reflect apparent aridification between ~4000 and 2000 cal years BP and have been associated with changes in the relative positioning of the southern westerly winds, and the strength of coastal upwelling in the Benguela Current system. At Groenfontein, the Holocene sequence is of a lower resolution but also suggests an important link between moisture availability and the strength of the southern westerly winds in the WRZ (Chase et al., 2023).

The expansion and/or strength of the southern westerly winds varies over time but has been shown to positively correlate to precipitation along South Africa's west coast, in the last 9000 years (Fletcher and Moreno, 2012), 2000 years (Kirsten et al., 2020), and 1200 years (Perren et al., 2020; Stager et al., 2012). Dilute diatoms at Verlorenvlei have been interpreted as indicators of westerly wind dynamics and track the addition of increased freshwater availability into Verlorenvlei (Kirsten et al., 2020; Stager et al., 2012). Therefore, the dominance of marine diatoms suggests reduced freshwater availability at Verlorenvlei during VER 1, likely reflecting a decreased influence of the southern westerly winds, reduced precipitation along the west coast, reduced fuel loads, and lower fire activity.

There is no evidence of pastoral herders in the region during this time and, although hunter-gatherers were potentially using fire as a foraging tool (Deacon, 1993), their population densities were low in the broader Western Cape (Fig. 4B; Parkington et al., 2021; Parkington, 1987, 2012). These low population densities suggest minimal anthropogenic impacts on local fire activity at Verlorenvlei during VER 1.

5.2. VER 2 (~2200–680 cal years BP)

The higher and less variable fire activity during VER 2 is associated with a shift from a marine-dominated diatom assemblage in VER 1 towards a brackish and freshwater-dominated diatom assemblage in VER 2 around 2000 cal years BP (Fig. 4D and E). Between 2500 and 1500 cal years BP, spanning the transition between VER 1 and VER 2, this diatom-assemblage shift suggests increasing moisture availability at Verlorenvlei (Kirsten et al., 2020). Fire activity similarly increases over much of this transition, tracking the increase in freshwater availability (Fig. 4D and E). Much work has highlighted the linkages between vegetation assemblages, increased winter rainfall, and equatorward shifts in the southern westerly winds across the region. Vegetation reconstructions from Verlorenvlei suggest that the xeric conditions of the early-mid-Holocene gave way to increased relative humidity during the late Holocene (Carr et al., 2015; Meadows and Baxter, 2001). Pollen data from Princessvlei suggests an increase in moisture at 1900 cal years BP evidenced by a decrease in Restionaceae and *Crassula*, and increases in Cyperaceae, Ericaceae, and *Staavia*-type pollen (Neumann et al., 2011). These shifts could be reflecting an increase in the groundwater table, or increased moisture availability. Using diatoms, Kirsten and Meadows (2016) document increased moisture at Princessvlei in the past 2100 years and attribute this shift to increased intensity of the southern westerly winds. A similar increase in winter moisture is identified between 2200 and 900 cal years BP at Rietvlei-Still Bay (Fig. 1; Quick et al., 2015). At Elands Bay Cave near Verlorenvlei, charcoal from xeric thicket taxa dominates after 1400 cal years BP (Cowling et al., 1999), which we interpret as increased fuel in this otherwise arid and fuel-limited site. The last 2000 years are also associated with increased westerly wind-derived regional moisture availability at Katbakkies Pass, Pakhuis Pass, and Groenfontein (Chase et al., 2015; 2019, 2023).

In the YRZ, changes in humidity ~2000 years ago at Seweweekspoort are also linked to shifts in the southern westerly winds (Chase et al., 2013, 2017). Geochemical data and grain size analyses from Eilandvlei suggest that increased precipitation after ~3000 cal years BP led to elevated river discharge, surface runoff, and weathering (Wündsch et al., 2018). An increase in brackish and freshwater diatoms after 3200 cal years BP further supports increased freshwater availability along the southern Cape coast in response to increased westerly influence (Kirsten et al., 2018).

Periods of high humidity in the WRZ are linked to cold events in Antarctica (Hahn et al., 2016; Stager et al., 2012). Southern Ocean sea surface temperatures were low between 2700 and 1700 cal years BP, related to increased sea ice in western Antarctica (Shevenell et al., 2011) and increased sea ice extent (Nielsen et al., 2004). Other southern hemisphere sites reflect a strengthening of the southern westerly winds in at least the past two millennia. In Chile's Gran Campo Nevado mountains, where precipitation is primarily driven by shifts in the southern westerly winds, increased hygrophytic pollen taxa suggest a widespread southern hemisphere response to strengthening and equatorward migration of the southern westerly winds over the last 2000 years (Fig. 4A; Lamy et al., 2010). In the Torres del Paine area of Patagonia, southern westerly wind-derived precipitation similarly increased over the past 2000 years (Moreno et al., 2018). These shifts towards colder conditions and extended Antarctic sea ice during the past 3000 years track a decrease in total solar irradiance that shifted the southern westerly winds equatorward, contracting the Hadley Cell (Riechelson et al., 2023). We suggest that large-scale ocean-atmosphere links resulted in strengthened southern westerly wind frontal systems that increased precipitation within parts of the WRZ and facilitated vegetation growth and more fire activity at Verlorenvlei. As a fuel-limited system, the Verlorenvlei area appears to support our hypothesis that increased moisture availability over the past ~4200 years increased fire by facilitating the development of increased biomass (i.e., fuel loads) (Alvarado et al., 2019; Karp et al., 2023).

The Medieval Climate Anomaly (MCA: 950–1250 CE or 1000–700 cal years BP; Mann et al., 2009) occurs towards the end of VER 2, though the reflection of the MCA in southern Africa is generally weak and inconsistent. At Verlorenvlei, the MCA begins with low fire, increases to slightly above-average fire, and subsequently decreases (Fig. 3A). At Bo Langvlei in the YRZ, the MCA was identified as relatively dry and slightly cooler than present (du Plessis et al., 2020), while at Orange Kloof in Table Mountain National Park, the MCA is not reflected clearly in the pollen record and appears to be a continuation of humid conditions that began ~650 CE (~1300 cal years BP; Prader et al., 2023). Despite these inconsistent climate signals, a weak fire response to the MCA may be expected as fire activity is driven primarily by relationships between moisture availability and fuel and not necessarily temperature.

In addition to these important climate dynamics, VER 2 spans the arrival of pastoralists into the region. Though evidence for domestic livestock dates to shortly before ~2000 cal years BP in southern Africa (Coutu et al., 2021), local evidence in the vicinity of Verlorenvlei is somewhat later. Sheep bones from Tortoise Cave suggest that pastoralists were present around 1530 cal years BP (2σ range: 1652–1408 cal years BP; Klein and Cruz-Uribe, 1987) and at Elands Bay Cave by 990 cal years BP (2σ range: 794–1179 cal years BP; (Klein and Cruz-Uribe, 1987, 2016). Older early sheep remains are found approximately 100 km to the south at Kasteelberg around 1750 cal years BP (Klein and Cruz-Uribe, 1989). Further to the southeast, older sheep remains are known from Die Kelders (Klein and Cruz-Uribe, 2000), Boomplaas (Deacon, 1979; von den Driesch and Deacon, 1985), and Blombos Cave (Henshilwood, 1996). Cattle appear later – around 1180 cal years BP (2σ range: 1295–1056 cal years BP) at Kasteelberg (Klein and Cruz-Uribe, 1989). Collectively, this evidence does not eliminate the possibility of pastoralists contributing to changes in fire shortly following their arrival into the region. But the timing of their arrivals suggests they may have followed the increasing moisture into further reaches of the semi-arid southwestern Cape, and arrived into an environment already experiencing elevated fire relative to the previous 2000 years.

5.3. VER 3 (~680 to -64 cal years BP; 1270–2014 CE)

The high and consistent burning of VER 3 includes the LIA (1400–1700 CE) and reflects a generally increasing trend in freshwater availability at Verlorenvlei (Carr et al., 2015; Kirsten et al., 2020; Stager et al., 2012). Increased moisture at Verlorenvlei during the LIA appears to have facilitated a larger increase in fire at Verlorenvlei, peaking between ~1550 and 1775 CE (Fig. 4D and E). This again suggests that increased precipitation fosters increased fire in this otherwise fuel-limited system. However, other WRZ and YRZ records during the LIA reveal inconsistent climate responses. At Erica Kuil, the period of 1100–1600 CE is represented by increased fynbos pollen taxa (Restionaceae, Ericaceae, Proteaceae) and a similar increase in fire activity suggesting increased fuel loads and an intensified fire regime (Manzano et al., 2023). At Orange Kloof in Table Mountain National Park, climate evolved towards lower humidity early in the LIA from 1250 to 1500 CE, resulting in fynbos expansion and Afrotemperate forest contraction (Prader et al., 2023). At Bo Langvlei in the YRZ, the LIA was clearly identified with cooler and drier conditions between 1600 and 1850 CE related to reduced precipitation from tropical systems (du Plessis et al., 2020). This spatial variability in the reflection of the LIA climate signal highlights the importance of applying local archives in this hydroclimatically diverse region.

Dutch colonists arrived in present-day Cape Town in 1652 CE and had widespread settlements by the mid-1700s CE (Noble, 1877). The period of highest fire activity at Verlorenvlei, beginning ~1550 CE, predates the timing of European arrival into the Cape, suggesting that this period of increased burning was not directly linked to their arrival (Fig. 4). However, fire activity is quickly reduced following the widespread settlement of Europeans in the mid-1700s CE when early Dutch botanists believed fire to be destructive and would result in deterioration of the landscape (Levyns, 1924; Marloth, 1924). Policies of fire suppression and the near elimination of Khoi pastoral practices likely resulted in a widespread and relatively rapid effect on fire activity, extending north towards Verlorenvlei. In addition to fire suppression, the arrival of Europeans had significant impacts on faunal communities. In the Western Cape, many native faunas were exterminated or nearly exterminated between 1600 and 1925 CE, including three megaherbivores (species >1000 kg), the black rhinoceros (*Diceros bicornis*), hippopotamus (*Hippopotamus amphibius*), and elephant (*Loxodonta africana*) (Radloff, 2008; Skead, 2011). It is likely that the disappearance of these large herbivores fundamentally changed vegetation communities, biomass availability, and fire activity in the CFR over this period (Holdo et al., 2009; Karp et al., 2021; Rowan and Faith, 2019). Since 1970 CE, many ungulates have been reintroduced, but the megaherbivore reintroductions were limited to reserves (Skead, 2011).

A decline in fire since ~1950 CE may be linked to a poleward shift in the southern westerly winds that has shifted this moisture source away from southern hemisphere continental landmasses and has resulted in decreased precipitation in Australia, western South Africa, and southern South America (Garreaud et al., 2009, 2019; Spinoni et al., 2014), bringing about drier conditions and diminished fuel loads. Examining the 20th-century impacts of climate change, fire suppression, urbanization, agriculture, and farming is beyond the scope of this paper, but warrants further investigation.

5.4. Drivers of fire activity at Verlorenvlei

Our linear model suggests that moisture availability is the most significant driver of fire at Verlorenvlei (Table 1). The second strongest model includes both moisture availability and people, but the relationship between fire and people is negative, meaning that more people on the landscape is associated with reduced fire activity. This is inconsistent with the expectation that more people result in increased ignitions and more fire, suggesting that the correlation is spurious. Based on this coarse proxy for human population densities in the region, we see no evidence that people played a decisive role in fire at Verlorenvlei. Thus, we favor the moisture-only model and see little evidence that the increase in fire ~2000 cal years BP is related to increased human population density on the landscape. The moisture-only model results align with our fire history reconstruction showing that fire activity began to increase ~2000 cal years BP, responding to a strengthening in the southern westerly winds and increased precipitation to the west coast (Fig. 4).

The arrival of pastoralists into the Verlorenvlei region could have influenced fire regimes independent of demographic change (Davies et al., 2022). Recent work suggests that pastoralists were present in parts of southern Africa shortly before 2000 cal years BP (Coutu et al., 2021), supporting the hypothesis that increased regional fire activity at this time coincides with archeological changes associated with human land use rather than climate (Davies et al., 2022). However, pastoralist occupations are documented slightly later in the vicinity of Verlorenvlei, closer to 1530 cal years BP at the earliest (Klein and Cruz-Uribe, 1987), and we see little evidence that their arrival was associated with greater fire (Fig. 3A). The difference between regional patterns (Davies et al., 2022) and the local-scale perspective from Verlorenvlei suggests that multiple processes, including climate and human activities, are shaping southern African fire regimes at different spatial scales.

The apparent disconnect between human populations and fire activity at Verlorenvlei is unexpected and merits further consideration. Changes in human use of landscapes in the area around Verlorenvlei may provide some explanation. Taphonomically corrected SPD estimates show increased population density beginning around 3000 cal years BP (Fig. 4B), corresponding with the onset of the "megamidden" period, where large concentrations of shells are found in many sites near Verlorenvlei (e.g., Jerardino, 1998). The significance of this archeological pattern is a subject of intense debate (e.g., Parkington et al., 2021; Jerardino, 2016; Parkington, 2016a), yet one possible explanation for this phenomenon is that hunter-gatherers were beginning to specialize in marine resources in a way that allowed them to become semi-sedentary (Jerardino et al., 2021). Under this scenario, the low levels of fire activity at Verlorenvlei during this time (Fig. 3A; VER 1) are surprising. However, another interpretation of this time frame is that hunter-gatherers were only making logistical forays into the Verlorenvlei region to collect shellfish and then returning to the inland areas (Parkington, 2012). In this scenario, the number of radiocarbon dates would overrepresent the actual human use of this landscape, implying a disconnect between the SPD data and human population size.

The end of the "megamidden" period, around 2000 cal years BP, sees a return to people living more intensively in rock shelters in the area around Verlorenvlei (e.g., Tortoise Cave) and there is some evidence that interactions between pastoralist and hunter-gatherer populations shifted hunter-gatherers further south, disrupting this pattern of transhumance around 2000 cal years BP (Loftus and Pfeiffer, 2023). It is possible that even though evidence of pastoralism is lacking in the Verlorenvlei area when fire incidence increases (Fig. 3A; VER 2), the impact of pastoralism in adjacent regions increased the intensity of land use in the vicinity of Verlorenvlei in the absence of demographic change. This emphasizes the need to interpret paleofire data within the context of both climate and archeological records. The integration of generative models with the empirical datasets may be a productive avenue for further exploring how fire regimes were shaped by changes in climate, human population sizes, and human landscape use through time (Braun et al., 2021).

6. Conclusions

This record is the first in the region to address the dual impacts of climate and humans on fire activity and tests previous hypotheses suggesting that pastoralist ignitions drove fire in the past 2000 years. Our reconstruction shows that increased moisture availability related to cooling Antarctic temperatures, equatorward shifts in the southern westerly winds, and increased frontal storms to Verlorenvlei likely facilitated increased fire by increasing fuel loads on the landscape. We find that fire activity increases alongside two periods of increased moisture availability related to a strengthening of the southern westerly winds: ~2000 cal years BP, and ~500 cal years BP (~1450 CE; the start of the Little Ice Age). Archeological excavations suggest that pastoralists arrived around Verlorenvlei ~1530 cal years BP, but this increase in population density occurs several centuries behind the initial increase in fire, suggesting that fire activity was already increasing in the area before the increased population densities. Linear regression modeling shows that moisture availability has significant impacts on the CFR fire activity and is the primary driver of burning. This work highlights linkages between climate-fuel-fire and people in South Africa's WRZ and may benefit land management and conservation decisions under future predictions of a warmer and drier southern Africa. Future work would also benefit from an improved understanding of the vegetation-fire dynamics at Verlorenvlei and increased resolution in late-Holocene WRZ hydroclimate and sea level change records.

CRediT authorship contribution statement

Stella G. Mosher: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mitchell J. Power:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Lynne J. Quick:** Writing – review & editing, Supervision, Resources, Investigation. **Torsten Haberzettl:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Thomas Kasper:** Writing – review & editing, Visualization, Software, Resources. **Kelly L. Kirsten:** Writing – review & editing, Investigation. **David R. Braun:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **J. Tyler Faith:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of 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.

Data availability

Data are available in the online supplement.

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Appendix A. Supplementary data

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