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Assessing changes in high-intensity fire events in south-eastern Australia using Fourier Transform Infra-red (FITR) spectroscopy

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ABSTRACT

Background. As fire regimes continue to evolve in response to climate change, understanding how fire characteristics have responded to changes in the recent past is vital to inform predictions of future fire events. **Aims and methods.** Using Fourier Transform Infrared (FTIR) spectroscopy, we assessed how fire intensity has changed in two fire-prone landscapes in south-eastern Australia: (1) the Blue Mountains; and (2) Namadgi National Park during the past 3000 years. **Key results.** Higher aromatic/aliphatic ratios suggest increased high-intensity fire frequency in sediments at the surface of both cores. Increases in the frequency of extreme drought periods, coupled with the change in vegetation and anthropogenic ignitions following colonisation, could have increased the frequency of high-intensity fires in the past ~200 years. **Conclusions.** FTIR spectroscopy can be used in sediment deposits to infer that the frequency of high-intensity fire events has increased in the past 200 years compared to the previous ~3000 years. **Implications.** These results are important for understanding how past fire regimes have responded to climate, people and vegetation shifts in the past ~3000 years and can be used to inform models for future predictions and management strategies.

Keywords: bushfires, carbon, climate, fire history, fire intensity, FTIR spectroscopy, sediments, Southeastern Australia.

Introduction

The annual cost of fires in Australia alone has been estimated at AUD8.5 billion, or 1.15% of the GDP (Sharples *et al.* 2016). Beyond the economic costs, fires also result in losses to cultural assets, threaten endangered flora and fauna, increase soil erosion, and reduce air and water quality (Worthy and Wasson 2004; Certini 2005; van der Werf *et al.* 2017). Fires are controlled by four fundamental factors: (1) fuel production; (2) fuel dryness; (3) fire weather; and (4) ignition sources (Bradstock 2010; Clarke *et al.* 2020). These have been referred to as the four 'switches' of a fire event, and the length of time that each is 'switched on' determines the potential for and characteristics of a fire (Bradstock 2010; Clarke *et al.* 2020). All four of these factors can be influenced by climate change, ultimately altering the fire regime (Pausas and Keeley 2021). Understanding how fire characteristics, such as severity (the degree of consumption of aboveground biomass) and intensity (the energy released and the heat transfer along the fire line during organic matter combustion) (Keeley 2009; McLauchlan *et al.* 2020), have changed through time could allow for a more systematic evaluation of the impact of fires on ecosystems and improve model predictive capabilities for future events (Whight and Bradstock 1999).

A strong correlation between the El Niño Southern Oscillation (ENSO) index and bushfire activity has been demonstrated for temperate south-eastern Australia (Mariani *et al.* 2016, 2018). The effects of ENSO occur across all seasons, where El Niño conditions during summer and autumn are more likely to increase the number of fires and burnt area (Mariani *et al.* 2016). A negative Southern Oscillation Index (SOI) during the winter and spring before the fire season reduces water availability, increasing the likelihood of lightning ignition (Mariani *et al.* 2016). The strong relationship between ENSO and bushfire activity, including burnt area and the number of fires, has also been demonstrated in Mediterranean Chile, western Mediterranean Australia, and temperate South America (Mariani *et al.* 2018 and references therein). Strong relationships were also found between the positive phases of the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM), especially in the 21st century (Mariani *et al.* 2018 and references therein). The most recent fires in 2019–2020 were considered unprecedented in the area burned and in severity across south-eastern Australia (Boer *et al.* 2020; Nolan *et al.* 2020). Existing predictions suggest that fire occurrences in the southern hemisphere may continue to increase as the strength of these modes continues to rise (Mariani *et al.* 2018).

Reconstructions of past fire events typically utilise techniques such as palynology, charcoal analysis, dendrochronology and photographic records (Conedera *et al.* 2009). More recently, satellite data have also been used to determine fire characteristics using various indices such as Normalised Difference Vegetation Index (NDVI) and Normalised Burn Ratio (NBR) (Hammill and Bradstock 2006; Malone *et al.* 2011; Gibson *et al.* 2020). However, despite the possible increases in the strength of the various climate modes, many existing reconstructions of fire activity span only short periods (~50 years); therefore, understanding how climate or other drivers might influence the overall fire regime over more extended periods is vital for determining if recent fire events (past 50–100 years) have burned at a higher intensity than has been experienced in the past. This will also improve predictive models of future fire events.

Fourier Transform Infrared (FTIR) spectroscopy has shown promising results in identifying past high-intensity fire events in soils (Simkovic *et al.* 2008; Lu *et al.* 2022; Šimkovic *et al.* 2023) and more recently, charcoal (Gosling *et al.* 2019; Constantine *et al.* 2021, 2023*a*, 2023*b*; Maezumi *et al.* 2021) and alluvial and swamp sediment deposits (Ryan *et al.* 2023; Ryan R, Dosseto A, Dlapa P, Thomas Z, Simkovic I, Mooney S, Bradstock R, unpubl. data). FTIR analyses spectral bands formed at specific wavenumbers when samples are exposed to infrared light, which can be attributed to particular functional groups (Smidt *et al.* 2005; Beć *et al.* 2020). Fire events increase the heterogeneity of soil organic matter through the transformation and partial destruction of the original components, resulting in the formation of new compounds (Mastrolonardo *et al.* 2015). Aliphatic compounds are the first to thermally decompose when exposed to a fire (González-Pérez *et al.* 2008; Abakumov *et al.* 2018). Decomposition of these aliphatic bonds typically occurs as temperatures exceed 250°C or with prolonged heating duration (Guo and Bustin 1998; Araya *et al.* 2017) to form more temperature and decomposition-resistant aromatic compounds (González-Pérez *et al.* 2008; Mastrolonardo *et al.* 2015). Due to the recalcitrant nature of these aromatic compounds, they are well preserved in sediment deposits, allowing for long-term reconstructions (El Atfy *et al.* 2017). This means that a ratio of aromatic/aliphatic peak area highlights the relative decrease in aliphatic compounds and subsequent increase in aromatic compounds. High values of the ratio can be used as a proxy for past high-intensity fire events, such as fires that scorch or consume tree crowns in eucalypt-dominated forests (Hammill and Bradstock 2006; De la Rosa *et al.* 2018; Ryan *et al.* 2023). We therefore hypothesise that as fire intensity increases, this will result in more significant increases in the aromatic/aliphatic ratio.

Here, we aimed to assess when and how the frequency of high-intensity fire events has changed during the past ~3000 years in two highly fire-prone landscapes in south-eastern Australia: (1) the Blue Mountains; and (2) Namadgi National Parks. Radiocarbon and Optically Stimulated Luminescence (OSL) dating were used to derive age-depth models. FTIR spectra were used to derive a record of high-intensity fire events, and results were compared against existing palaeoclimate reconstructions to investigate the links between climate variability and fire history. Increasing our understanding of how the fire regime behaved in the past can improve models of fire events to better predict how they may change in the future.

Materialas and methods

Study area

Namadgi National Park was established in 1984 and is approximately 50 km south-west of Canberra, encompassing approximately 46% of the Australian Capital Territory (ACT) (Salmona *et al.* 2018). It is situated in the southern part of the Lachlan Fold Belt, with elevations between 900 and >1900 m above sea level (m.a.s.l.). It forms the northernmost extent of the Australian Alps (Department of Territory and Municipal Services 2007; Theden-Ringl 2016). Granites dominate along ridges and slopes, whilst Ordovician sediments predominate at lower elevations around the Cotter River and its tributaries (Peat *et al.* 2005; Nichols *et al.* 2006). Soils are typically shallow and highly susceptible to erosion once disturbed (Carey *et al.* 2003). The vegetation of the region is characterised by sclerophyll forest where *Eucalyptus* species form the canopy and grasses and herbs form a dense understorey, and subalpine woodland (Pryor 1939). Whilst pine plantations in Boboyan were rehabilitated as part of the 1986 Namadgi Plan of Management (National Capital Development Commission 1986), plantations are still present within the Lower Cotter Catchment and are a source of higher sediment loads to catchment tributaries (Daniell and White 2005; Kasel and Bennett 2007; Wade *et al.* 2013). The temperate climate results in cold winters where snow persists on the higher parts of the ranges, and summers are warm (Nichols *et al.* 2006; Department of Territory and Municipal Services 2007). An absence of rain and low relative humidity results in favourable conditions for fire spread (Caccamo *et al.* 2012; Nolan *et al.* 2016).

There is evidence of the Indigenous occupation of Namadgi National Park for at least the past ~20,000 years (Carey *et al.* 2003; Salmona *et al.* 2018; Theden-Ringl *et al.* 2023). Dendrochronology of snow gum (*Eucalyptus pauciflora*) trees suggests that before 1830, fires occurred every 25 years; however, between 1830 and 1959, this increased to one fire every 3–4 years (Banks 1989; Zylstra 2006). Due to the short return interval between fire events from 1830 to 1959, it is unlikely that all of these fires were high-intensity bushfires, however the exact intensity is unknown (Banks 1989; Zylstra 2006). Land cover change associated with pastoralism and agricultural practices significantly increased fire frequency during this period (Banks 1989; Zylstra 2006; Salmona *et al.* 2018). Keaney (2016) also claims that gold miners used fire to clear land. In more recent years, fire management of Namadgi National Park has focused on suppression with some prescribed burning to aid asset protection (Carey *et al.* 2003). Since British colonisation, major fire events occurred in 1876, 1881, 1892, 1920, 1926, 1939, 2002–2003, and 2019–2020 (Salmona *et al.* 2018).

The Blue Mountains are ~60 km west of Sydney and are included within the Greater Blue Mountains World Heritage Area (Cunningham 1984; Chapple *et al.* 2017). The Blue Mountains were designated as a national park in 1959, with later amendments to extend its area (NSW National Parks and Wildlife Service 1998). Rising to ~1300 m a.s.l., the Blue Mountains are characterised by shales, coal measures and sandstones of Permian and Triassic age (Cunningham 1984; Freidman and Fryirs 2015). The soils are thin and sandy (Dragovich and Morris 2002; Keith 2004), and the vegetation consists largely of dry sclerophyll woodland and open forests, where *Eucalyptus* species dominate. Small patches of tall open forest and wet sclerophyll forest are primarily restricted to gorges (Keith 2004), which also offer some protection from fire events. Annual precipitation is 900–1000 mm, with sleet and occasional snow during winter and strong winds during warm summers (Wilkinson *et al.* 2005). Like Namadgi, short-term decreases in precipitation and relative humidity can rapidly increase dry fuel connectivity, subsequently increasing the potential for large fire events (Caccamo *et al.* 2012; Nolan *et al.* 2016).

Although written history is scarce, it is possible that the Blue Mountains was traditionally burnt at a lower intensity by the Gundungarra people or ignited by lightning. However, more recently, the fire regime has shifted to high-intensity fire events with some prescribed fires for fuel management (Cunningham 1984; Dragovich and Morris 2002; Black *et al.* 2006). Topography has been a significant barrier to fire management in the Blue Mountains, with large sections of bushland remote or inaccessible for fire-fighting efforts (Cunningham 1984). During the known history, major bushfires and megafires have burnt in the Blue Mountains in 1957, 1968–1969, 1982–1983, 1984–1985, 1993–1994, 1997–1998, 2001–2002, 2002–2003, 2013, and 2019–2020 (Cunningham 1984; Tasker and Hammill 2011; Morgan *et al.* 2020).

Namadgi National Park and the Blue Mountains both host threatened ecological communities, including Alpine Ash forests and Temperate Highland Peat Swamps on Sandstone (THPSS), respectively (Chalson and Martin 2009; Webb 2011; Doherty *et al.* 2017; Fryirs *et al.* 2021). They are also highly fire-prone landscapes. In Namadgi, we focused on sediments accumulated on the floodplain of the Cotter River at the intersection with De Salis Creek (Fig. 1). The site was burnt in the 2002–2003 and 2019–2020 bushfires. Sediments from swamp deposits in Namadgi National Park have shown that fire has been a persistent feature since the formation of the swamps (Hope 2006), whilst sediments from the Cotter River have shown a clear relationship between fire occurrence and climate (Worthy 2013). In the Blue Mountains, we focused on Urella Brook Swamp (UBS-01), one of the THPSS (Fig. 1). The UBS-01 catchment area was burnt in 1982–1983, 1993–1994, 2002–2003 and 2019–2020 bushfires, and a prescribed burn was undertaken in 2015–2016. Existing studies from THPSS have found alternating organic and inorganic bands controlled by catchment stability, rainfall and fire (Fryirs *et al.* 2014; Mooney *et al.* 2021). The sedimentation rate in this environment is typically low, highlighting reduced erosion, infrequent or low-severity fires and vegetation stability (Mooney *et al.* 2021).

Sample collection

In Namadgi, a 75-mm diameter sediment core was collected at the CR-01 site (35.610396°S, 148.822151°E), reaching 77.5 cm deep. The site of sediment collection was carefully targeted to minimise loss by erosion from the river for a more complete record. The treeline, dominated by dry sclerophyll forest, was located to the west of the site, whilst the river was situated approximately 5 m to the east of the site. The core was split vertically down the middle to produce two identical halves, one of which was subsampled at a resolution of 1 cm for analysis (Supplementary Fig. S1).

In the Blue Mountains, the UBS-01 site (33.6503°S, 150.3920°E) was sampled such that creek lines (situated 2 m south of the site) and channels were avoided to ensure a more complete record. The forest slopes above the site, hypothesised to be one of the primary sediment sources to the swamp, was ~7 m north of the site. The swamp itself was dominated by heath vegetation. A 24-cm deep monolith was collected and split in half vertically. One half of the bulk was subsampled at 1 cm resolution for analysis (Fig. S1).

Age-depth model determination

Four charcoal subsamples were radiocarbon-dated from the CR-01 core. Three charcoal subsamples were isolated using wet-sieving from the sediment from the top (2–3 cm), middle (13–14 cm), and bottom (21–24 cm) of the UBS-01 monolith, along with a seed from 2–3 cm. Accelerator Mass Spectrometry (AMS) was performed at the Chronos

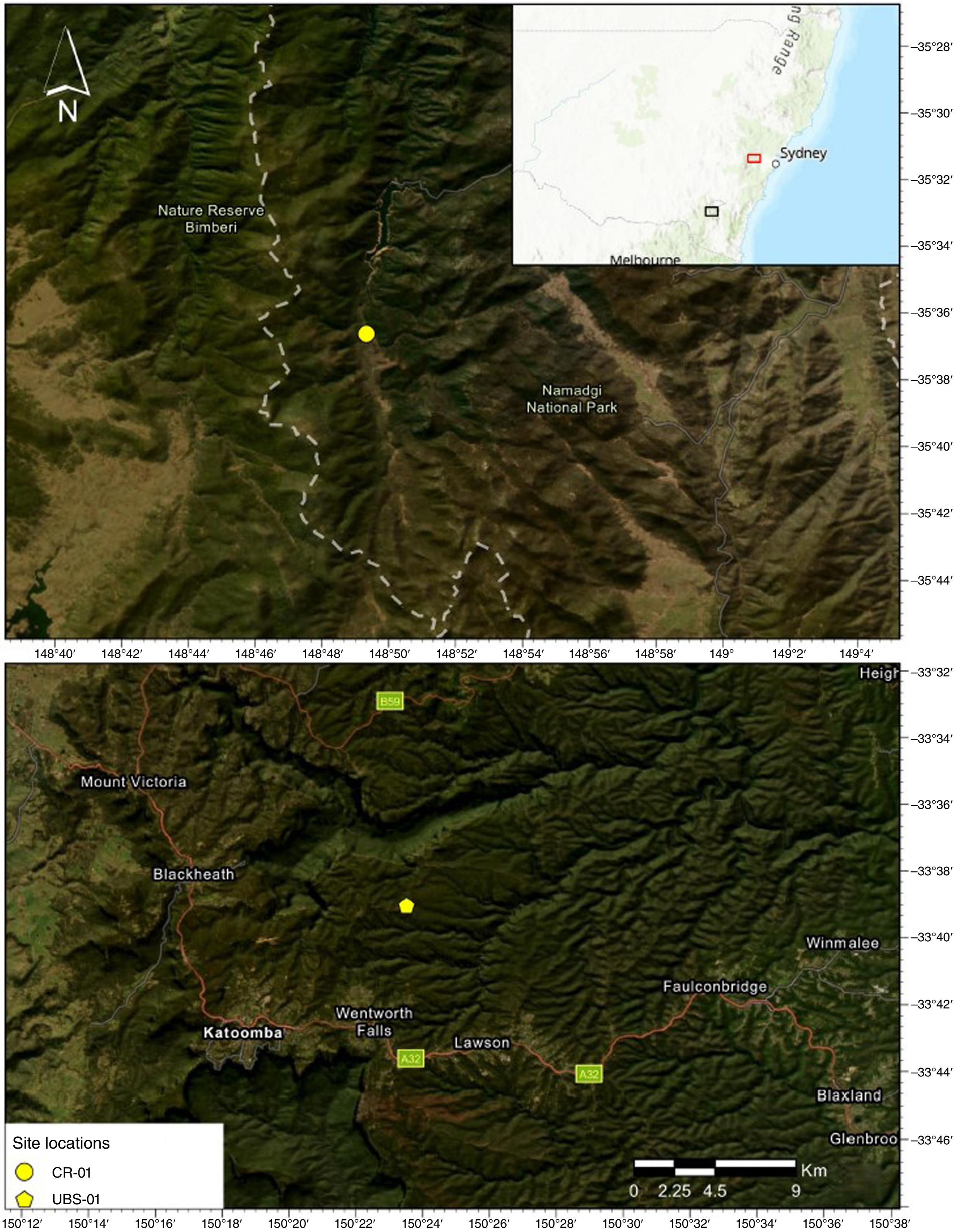

Fig. 1. Study site locations of the Cotter River (CR-01; yellow circle) in Namadgi National Park (black extent) and Urella Brook Swamp (UBS-01; yellow pentagon) in the Blue Mountains (red extent). Satellite Image: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN and the GIS User Community Esri, HERE, Garmin, OpenStreetMap contributors and the GIS User Community.

^{14}Carbon-Cycle facility, at the UNSW Sydney. The charcoal subsamples were prepared using an acid-base-acid treatment at 80°C with 1 M HCl and 0.2 M NaOH, following Turney *et al.* (2021). Due to the size and fragility of the seed subsample, no pre-treatment was applied; instead, it was rinsed with Milli-Q water before being graphitised for analysis. Since chemical pre-treatment of the seed was not possible, it likely represents a minimum age.

For the CR-01 core, in addition to C-14 dating, optically stimulated luminescence (OSL) dating was performed previously by Worthy (2013). Quartz grains between 180 μm and 212 μm were isolated and acid-washed with HCl and HF. Where necessary, heavy minerals were removed using sodium polytungstate. This was followed by HF leaching with a small volume of HCl to avoid calcium fluoride formation. Subsamples were analysed using a Risø TL-DA-15 MiniSys II at the Australian National University. Single-grain measurements were made using the 532 nm laser, and all signals were detected using an EMI 9235QA PMT filter. The beta dose rate for each subsample was calculated using ICP-MS measurement of U, Th and K content, and the gamma dose rate used was simply twice the measured 2π geometry at the surface of each subsample. The subsample depth was used to calculate the cosmic dose rate contribution using the formulae of Prescott and Hutton (1994). The equivalent dose was calculated with the Analyst software (ver. 3.24), and the minimum age model ages were used in conjunction with the radiocarbon dates for the age-depth model.

The radiocarbon and OSL ages were input into Oxcal 4.4, a Bayesian model employing Markov Chain Monte Carlo simulations (Bronk Ramsey 2009). The 'P_sequence deposition model' was used with the charcoal outlier model applied to the charcoal subsamples (Bronk Ramsey 2009). The OSL dates were converted to a format comparable to the radiocarbon ages for incorporation into the model. The year of sampling at 0 cm was input into the model as an upper constraint, and the 'combine' function was used at 2–3 cm for the seed and charcoal ages in the UBS-01 core. The 'SHCal 20' and 'Bomb 21 SH12' calibration curves were used to generate a calendar age-depth model (Hogg *et al.* 2020; Hua *et al.* 2021).

FTIR spectroscopy by KBr pressed discs

All subsamples (n = 100) and replicates (n = 5) were analysed for FTIR spectroscopy by KBr pressed discs at Comenius University using a Nicolet 6700 FTIR spectrometer and OMNIC 8 software (Thermo Fisher Scientific). Approximately 1 g of the bulk sediment from each depth was ground to a fine, homogenous powder using a zirconium oxide mill and then dried at 60°C for 24 h. A total of 2 mg of each subsample was combined with 200 mg of KBr and pressed into a pellet. Measurements were conducted in transmission mode across the 4000–400 cm^{-1} range. Scans (n = 128) were averaged for each subsample at a resolution of 2 cm^{-1}, and the results were reported as absorbance values. The averaged spectra were baseline corrected in Python 3.8 using the 'arPLS' method (Baek *et al.* 2015) in the 'RamPy' package (Le Losq 2018). All subsamples produced spectra that were able to be interpreted. The baseline-corrected spectra were analysed for changes in the peak area ratio, determined by taking the area under the curve for aromatic compounds (1750–1500 cm^{-1}) (Keiluweit *et al.* 2010; Guénon *et al.* 2013) and aliphatic bonds (3000–2800 cm^{-1}) (Guo and Bustin 1998; Ellerbrock *et al.* 2005; Lammers *et al.* 2009) for each subsample. Significant increases in the aromatic/aliphatic ratio were identified as ratio values >2 s.d. from the mean and identified as fire-affected sediments. Since the CR-01 core represents a longer record, a change point analysis, using the 'ggchangepoint' package in RStudio (Killick and Eckley 2014), was used to identify key periods of significant change (see Supplementary Fig. S4). The peak area ratio values were then normalised to values between 0 and 1 in RStudio to facilitate comparison between sites.

Elemental analysis

Elemental analysis of carbon (C) was conducted at the Wollongong Isotope Geochronology Laboratory (WIGL) using an Elementar Vario Macro Cube Element Analyser. 50 mg of each subsample was ground to a fine and even powder for analysis. Three phenylalanine standards of different masses were analysed at the start of the sequence to formulate a calibration curve. Two blanks were also analysed prior to the phenylalanine standards and one blank before the samples. A repeat was analysed every four samples (n = 11), and a phenylalanine standard every 10–15 samples to account for drift. Carbon concentrations are reported in weight percent (wt%).

Results

Cotter River

A combination of radiocarbon and OSL dates between depths of 0 and 97 cm for the CR-01 site resulted in 28 ages used in the final age-depth model (Table S1, Fig. S2). This suggests that the CR-01 core covers the past ~3000 years, with the sedimentation rate decreasing with increasing depth (Fig. S3*c*) and ranging from 0.0175 to 0.192 cm/year.

Aromatic to aliphatic ratios in the CR-01 sediments varied from 3.0 to 14.3. The changepoint analysis identified three regions where peaks were considered, and subsamples with values >10.7 (0–25 cm), >10.0 (25–52 cm), and >8.4 (52–77 cm) were considered fire-affected sediments in the CR-01 site (Fig. 2*a*). Peaks in the top ~23 cm, corresponding to the past ~200 years in the age-depth model, show the highest peak area ratio values, and the number of years

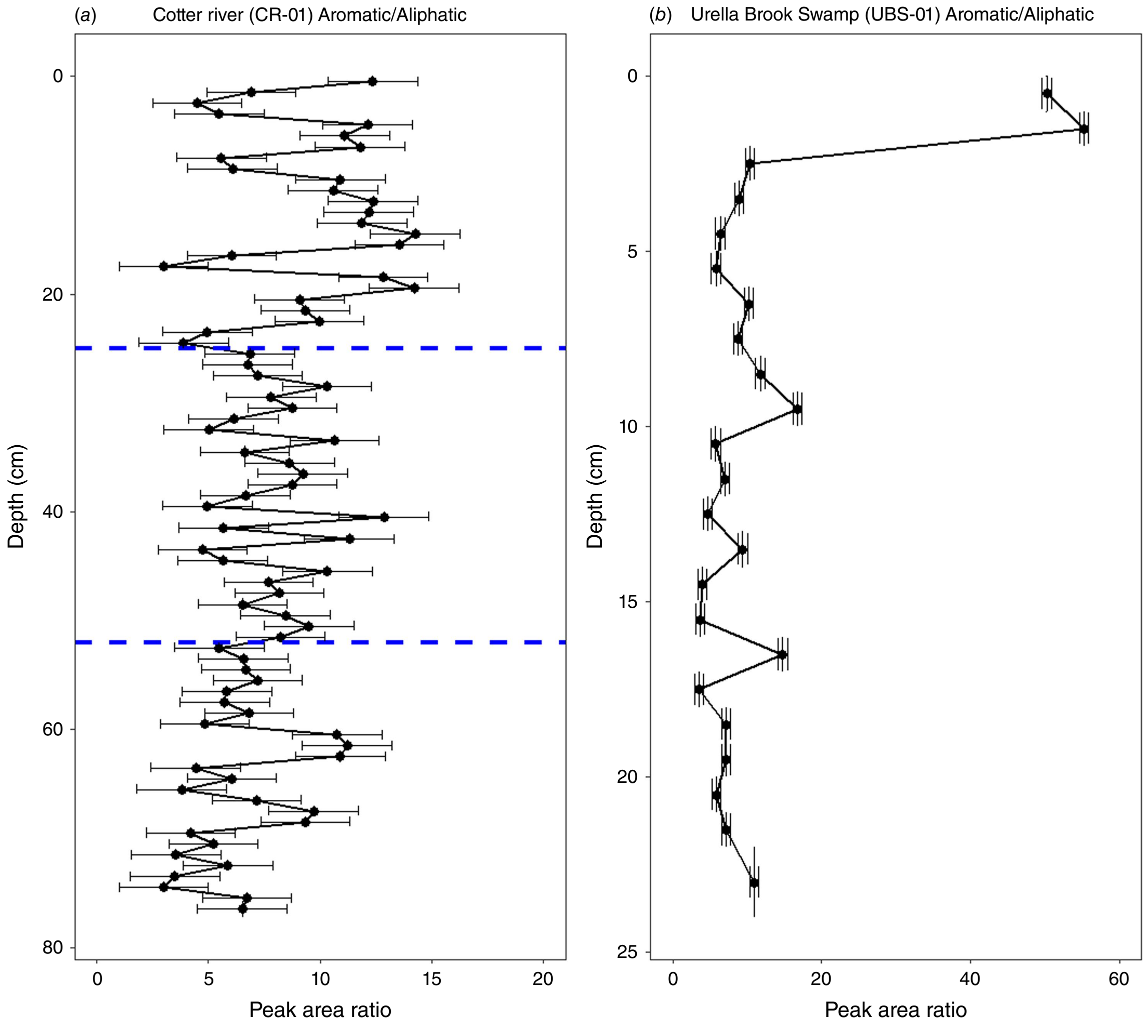

Fig. 2. Aromatic/aliphatic ($A_{(1750\text{–}1500\text{cm}^{-1})}$)/($A_{(3000\text{–}2800\text{cm}^{-1})}$) peak area ratios for (*a*) Cotter River (CR-01) and (*b*) Urella Brook Swamp (UBS-01) as a function of sediment depth (in cm). Blue dotted lines represent the zones used for peak identification values where key periods of change were identified by a change point analysis using the 'ggchangepoint' package in RStudio (Killick and Eckley 2014) (see text for details).

between each of these peaks is shorter compared to the remainder of the core. Carbon content ranges from 0.1 to 9.78 wt%.

Urella Brook Swamp

Four radiocarbon ages were used to generate the final age-depth model for the UBS-01 site (Ryan R, Dosseto A, Dlapa P, Thomas Z, Simkovic I, Mooney S, Bradstock R, unpubl. data) (Table S1, Fig. S2). The UBS-01 site covers the past ~500 years, over which time sedimentation has remained relatively constant (Fig. 3*a*), ranging from 0.0596 cm/year at the surface of the monolith to 0.0522 cm/year at 22–25 cm depth. The sedimentation rate of the UBS-01 site is slower than that of the CR-01 core.

Aromatic to aliphatic ratios varied from 3.6 to 55.3, which is much higher than the CR-01 site. This is possibly due to the site's higher organic matter content, shown by the carbon content, which ranges from 6.17 to 40.64 wt%. For most of the core, values were relatively low and constant, averaging ~7.3. For the UBS-01 site, fire-affected sediments were associated with ratio values of >12. Peaks were identified at 0–1, 1–2, 9–10 and 16–17 cm, with values of 50.3, 55.3, 16.7, and 14.8, respectively (Fig. 2*b*). This corresponds with dates of 2017 (+2/−10) CE, 2011 (+3/−31) CE, 1882 (+84/−101) CE, and 1737 (+157/−121) CE from the model (Ryan R, Dosseto A, Dlapa P, Thomas Z, Simkovic I, Mooney S, Bradstock R, unpubl. data). A small increase in the frequency of high-intensity fire events is also apparent in the UBS-01 site.

Discussion

The aromatic/aliphatic ratio is a proxy for high-intensity fire events, identifying sediments exposed to these conditions. Aliphatic compounds begin thermal decomposition at temperatures >250°C, or as the heating duration increases, to form more condensed, decomposition-resistant aromatic compounds (Vergnoux *et al.* 2011; Mastrolonardo *et al.* 2015; Merino *et al.* 2015; Araya *et al.* 2017; Abakumov *et al.* 2018). As fire severity increases in forested catchments, more woody material is burnt, further increasing relative aromatic contributions (Guo and Bustin 1998; Nocentini *et al.* 2010; Esfandbod *et al.* 2017). Whilst aromatic C is predominant in the band at 1750–1500 cm^{-1}, there can also be some contributions from bending vibrations of water between phyllosilicate layers (Madejová 2003). However, there is a strong positive correlation between C content and the peak area of aromatic absorption for both sites, with correlation coefficients of 0.656 and 0.909 for CR-01 and UBS-01, respectively, suggesting aromatic C is more dominant in this band (Fig. S5). Therefore, we assume that sediments with high values of the ratio can be used as a proxy for past high-intensity fire events. We also assume that the higher the aromatic/aliphatic ratio values at a given site, the more intense the fire event was. Due to the differences in organic matter content between the two sites, the peak area ratio results were normalised to allow comparison of peak intensity between sites.

The existing fire record derived from remote sensing data spans the past ~65 years for both sites (State Government of NSW and NSW Department of Climate Change, Energy 2010; Hammill *et al.* 2013); therefore, the sediments collected at each site extend this record by centuries to millennia. Over this period, the most significant change in the frequency of assumed high-intensity events has occurred in the past ~200 years. We propose three possible drivers for the change in fire regimes: climate, people and vegetation.

Climate variability

The sediment sampled from the CR-01 site records the past ~3000 years. Age uncertainties are small for the majority of the core (<200 years); however, age uncertainties increase for ages older than ~2000 years. These age uncertainties are comparable to many of the palaeoclimate records considered here, and therefore interpretations based on these records can be made with a similar degree of confidence. Sediments recording the period between 3000 and 2000 cal year BP in the CR-01 core showed an increased number of years between high-intensity fire events detected by the aromatic/aliphatic ratio compared to the remainder of the core (Fig. 3*a*). Records from the Kosciuszko region also highlight broad-scale climate instability during this period (Martin 1986; McGowan *et al.* 2018; Hope *et al.* 2019). Previously analysed swamp sediments in Namadgi National Park have shown a high charcoal influx, and the chemical signatures identified reduced net primary productivity from 2500 to 2200 cal year BP (Theden-Ringl *et al.* 2023). These characteristics have been hypothesised to record the start of a series of extreme and prolonged El Niño events (Gagan *et al.* 2004). Sediments at 67–69 cm depth in the CR-01 core are within error of this period and show a peak in the aromatic/aliphatic ratio, suggesting that the fire events occurring during this period burnt at relatively high intensity. These peaks at 67–69 cm give values of ~9.3–9.7 (normalised values of 0.56–0.60), which is smaller than peaks in the sediments recording more recent fire events, suggesting that, whilst these fires between 2500 and 2200 cal year BP burnt at a high intensity, more recent fire events burnt at higher intensities.

A peak in the aromatic/aliphatic ratio is evident in sediments recording ~1800 cal year BP in the CR-01 core. Drier conditions have been suggested during this period (Martin 1986), and fuel dryness is one of the four ‘switches’ controlling fire occurrence (Bradstock 2010; Clarke *et al.* 2020). If fuels are available and sufficiently dry, this increases the likelihood of fire ignition by both natural (lightning) and anthropogenic sources and fire spread (Flannigan *et al.* 2000). This could result in the high-intensity fire recorded in the CR-01 core during this period.

Several peaks are also evident in the aromatic/aliphatic ratio of the sediments recording the period from 1650 to 1000 cal year BP in the CR-01 core, particularly around 1200–1000 cal year BP, suggesting increased high-intensity fire frequency in the catchment. This agrees with existing studies of Club Lake in the Snowy Mountains region of Australia, which suggests a warmer period from 1650 to 1000 cal year BP, resulting in an expansion in *Eucalyptus* sub-alpine woodland and a reduction in alpine species (Thomas *et al.* 2022). This period also saw increased charcoal, suggesting increased fire activity (Thomas *et al.* 2022). Following this period, a decline in high-intensity fire events recorded by FTIR is apparent in the CR-01 core, indicated by a reduction in the number of peaks in the aromatic/aliphatic ratio.

The period between ~1500 and 1840 CE corresponds with the occurrence of the Little Ice Age in the Northern Hemisphere. While this cooling did not have as great an impact in the Southern Hemisphere, lower fire frequency has been identified from tree ring reconstructions in the Australian Alps (Zylstra 2006). This was suggested to result from cooler temperatures and a possible reduction in dry lightning ignitions during this period (Zylstra 2006). Furthermore, the East Australian and New Zealand Drought Atlas (ANZDA) identified a spatially consistent wet period from ~1750–1800 CE (Palmer *et al.* 2023), also suggesting reduced potential for dry lightning and

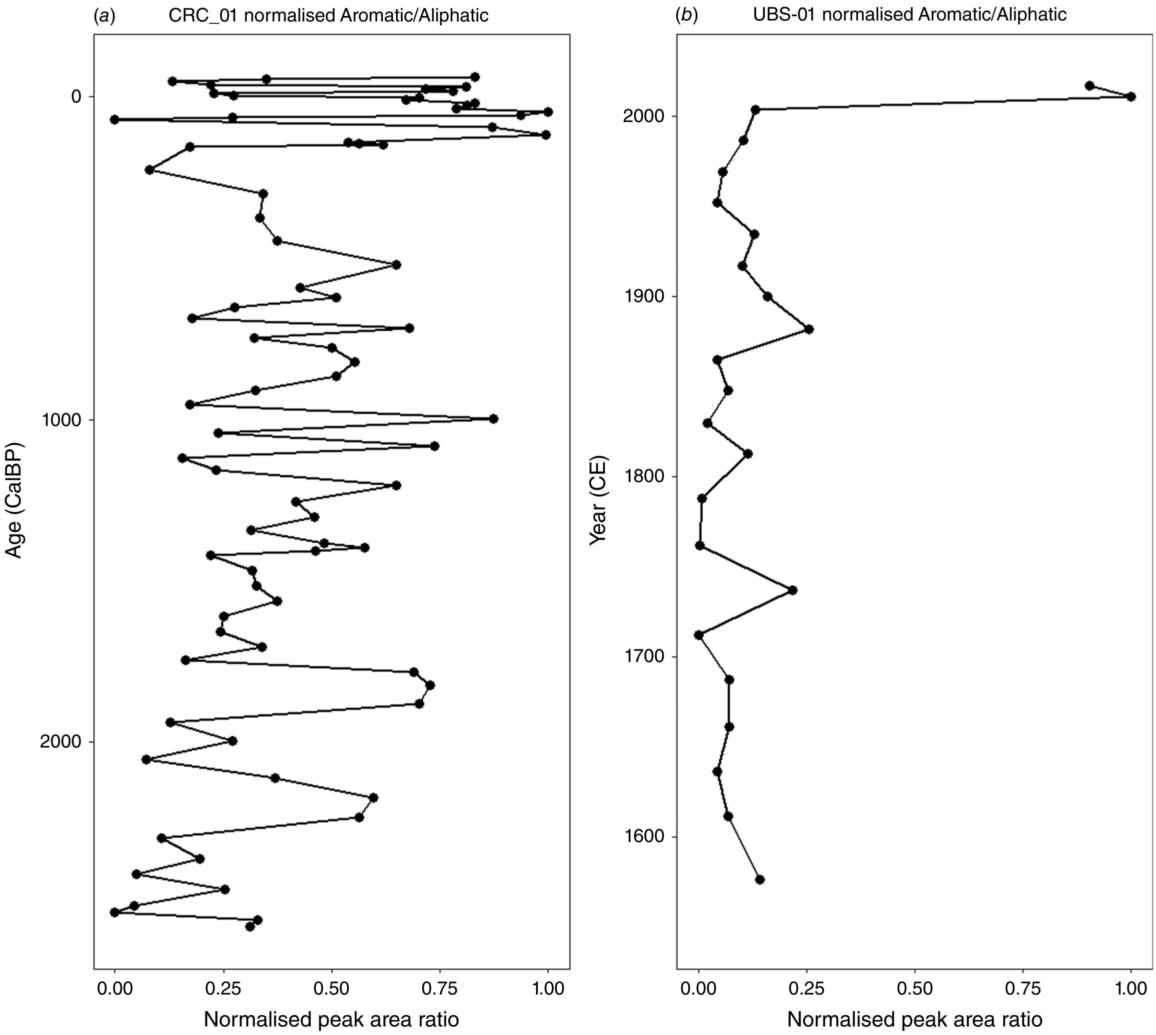

Fig. 3. Normalised aromatic/aliphatic ($A_{(1750–1500 cm^{-1})}$)/($A_{(3000–2800 cm^{-1})}$) peak area ratios for (*a*) Cotter River (CR-01) and (*b*) Urella Brook Swamp (UBS-01) as a function of the modelled sediment deposition age in CE (UBS-01) and CalBP (CR-01), respectively.

anthropogenic ignitions. The UBS-01 site also records this period from ~1500 to 1840 CE and shows only one high-intensity fire event (Fig. 3*b*). It is possible that the Australian Alps, including Namadgi National Park, could have experienced a greater extent of cooling than the Blue Mountains due to its higher altitude and latitude. Alternatively, fires may have burned at a lower intensity or in other sections of Namadgi National Park and were not recorded in the FTIR spectra.

For the sediments recording the past 200 years, we have primarily compared changes in the frequency of high-intensity fire events with the ANZDA for past climate information. The ANZDA divides Australia into 54 natural resource management (NRM) clusters (Palmer *et al.* 2023). The CR-01 site is located in the Murray Basin cluster, where extreme rain events and droughts have become more frequent during the past 200 years (Fig. 4). Prolonged drought events promote fire activity in forested ecosystems by reducing the number of natural barriers to fire spread (Bradstock *et al.* 2009). Fuels in these environments are typically too moist to burn; however, during a drought, dead fuel moisture decreases rapidly, increasing dry fuel connectivity (Caccamo *et al.* 2012; Nolan *et al.* 2016). Live fuels dry more slowly in response to soil moisture content, therefore, more prolonged droughts can further increase available fuel loads (Nolan *et al.* 2016). This increase in prolonged events could account for the increase in the frequency of high-intensity fires suggested by peaks in the aromatic/aliphatic ratio of the CR-01 core.

The UBS-01 site is located in the East Coast NRM cluster (Fig. 5). The increase in the frequency of extreme climate events in this NRM is less pronounced than in the Murray Basin NRM; however, it is still notable, particularly the drought event in the period ~2000–2010 CE. This increase in drought events is within error of the aromatic/aliphatic ratio peaks corresponding to 2017 (+2/−10) CE and 2011

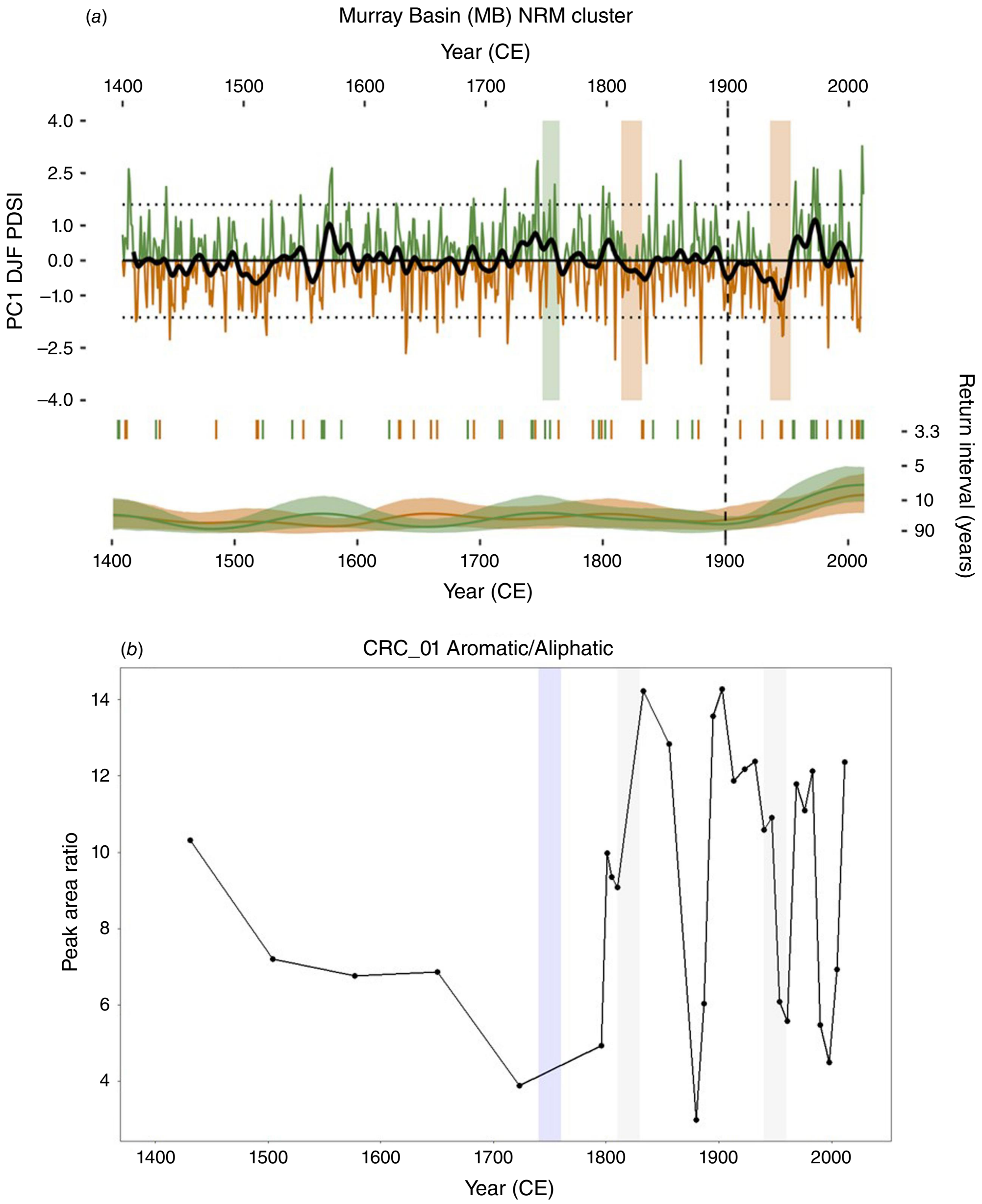

Fig. 4. (*a*) Palmer drought severity index (PDSI) values for the Murray Basin natural resource management (NRM) cluster between 1400 and 2012 CE where brown bars represent prolonged drought events and green represents prolonged wet periods events (adapted from Palmer *et al.* 2023). The dotted line at 1900 CE represents the division between the instrumental and palaeo record (Palmer *et al.* 2023). The extreme years are highlighted as a bar chart, and the data from these extremes were used to plot a time-varying frequency of extreme occurrences, which is represented by the return intervals (years) (Palmer *et al.* 2023). (*b*) The aromatic/aliphatic ratio values for sediments recording between 1400 and 2012 CE in the CR-01 core. Grey bars representprolonged drought events; blue bars represent prolonged wet periods.

(+3/−31) CE. Age uncertainties for these depths within the monolith are small. Therefore, confidence in the correlation between these fire events and this drought period is high, and this increase in the frequency of extreme droughts could explain the increased frequency of high-intensity fire events in the past 200 years at both sites.

People

The recent increased frequency of high-intensity fire events may also be linked to changed land management between pre- and post-colonial periods. Whilst high-intensity fire events are recorded throughout the entire CR-01 core, the

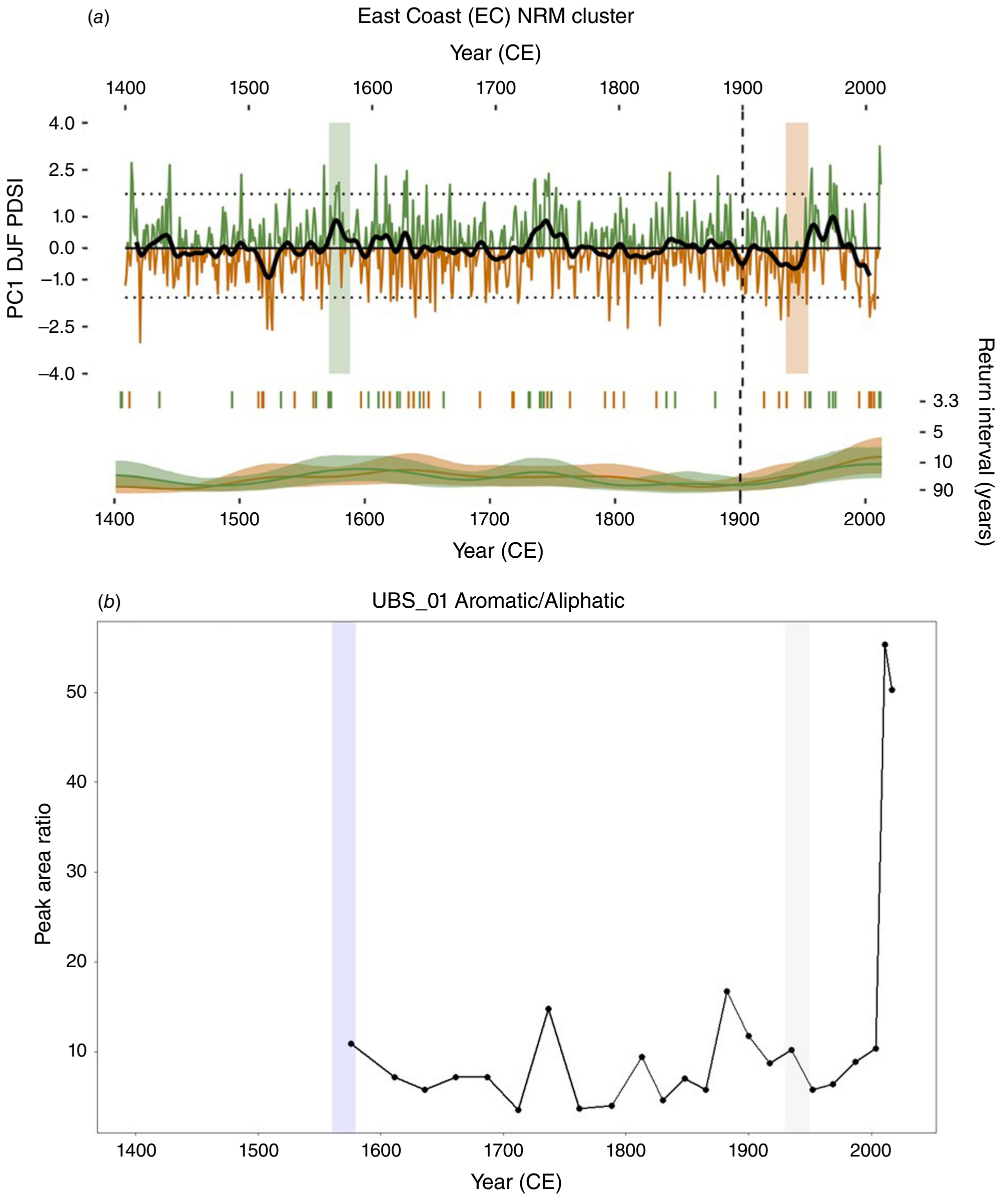

Fig. 5. (*a*) Palmer drought severity index (PDSI) values for the East Coast natural resource management (NRM) cluster between 1400 and 2012 CE where brown bars represent prolonged drought events and green represents prolonged wet periods events (adapted from Palmer *et al.* 2023). The extreme years are highlighted as a bar chart, and the data from these extremes were used to plot a time-varying frequency of extreme occurrences, which is represented by the retune intervals (years) (Palmer *et al.* 2023). The dotted line at 1900 CE represents the division between the instrumental and palaeorecord (Palmer *et al.* 2023). (*b*) The aromatic/aliphatic ratio values for sediments recording between 1575 and 2012 CE in the UBS-01 core. Grey bars represent prolonged drought events, and blue represents prolonged wet periods.

peaks corresponding with the past 200 years have the highest values, suggesting an increase in fire intensity. Existing studies show that fine charcoal has been present throughout the entire, however, during the Holocene, snow gum woodlands at higher altitudes were seldom burnt (Hope 2006; Zylstra 2006; Hope *et al.* 2009). Instead, fires were restricted to the montane forests and lower altitude grasslands and shrublands, with the precise frequency unknown (Theden-Ringl *et al.* 2023). Following European arrival ~1840 CE, charcoal significantly increased in response to burning to clear land for agriculture and pastoralism (Salmona *et al.* 2018). This is also seen in dendrochronological records, which suggest that before colonisation major landscape-scale fires occurred approximately every 80 years, however, following European colonisation, fire frequency increased significantly (Banks 1989; Burrows *et al.* 1995; Zylstra 2006). In ~1935 CE, charcoal decreased to much lower levels as fire suppression for management increased (Hope 2006; Hope *et al.* 2009).

The older two detected peaks in the UBS-01 site, reflecting fires in 1737 (+157/−121) CE and 1882 (+84/−101) CE, respectively, occurred before and after the colonisation of the Blue Mountains; these older two peaks show a similar aromatic/aliphatic ratio value, suggesting comparable intensity. However, the aromatic/aliphatic ratio values for the most recent detected fires are up to 3× larger than the older two detected fires. This suggests a possible delay in anthropogenic impacts in the Blue Mountains region or the result of the interaction between another driver in conjunction with land management changes. Whilst cultural burning was used for a range of localised activities in the Blue Mountains, these practices may have indirectly modified the occurrence of extreme fire events and vegetation structures (Chalson and Martin 2009; Constantine *et al.* 2023*a*). Swamp records from Goochs Crater suggest that climate was a more dominant factor, rather than anthropogenic uses of fire during the past ~14,000 years (Black and Mooney 2006). Recent anthropogenic ignited fires, including arson, prescribed fires that break containment lines and agricultural fires, have more frequently coincided with extreme fire weather (Seydack *et al.* 2007; Bradstock 2008), such as extended drought periods, as mentioned in the previous section, suggesting the interconnection of these drivers in increasing fire intensity.

Vegetation change

Changes to vegetation composition in response to climate and anthropogenic influence could also contribute to the increased frequency of high-intensity fire events observed at both sites. Existing studies analysing pollen from sediment cores from swamps in the Blue Mountains and Namadgi regions have identified vegetation change throughout the Holocene, the most substantial occurring in the past 100 years following European colonisation (Black *et al.* 2006; Hope 2006; Hope and Clark 2008; Chalson and Martin 2009). In Namadgi National Park, Hope (2006) found an increase in introduced herbaceous weed species such as cats ear (*Hypochaeris radicata*), followed by the appearance of *Pinus radiata* pollen at all swamp sites analysed, marking the early impacts of European pastoralism and agriculture. Eucalypt representation has increased in abundance in the Namadgi region, reducing the prominence of grass (Hope 2006; Hope and Clark 2008). The surface fuels of eucalypt forests are not homogenous, instead, the fuels are stratified with a compact surface layer with a more aerated layer above, which increases fuel continuity and fire spread (Gould *et al.* 2011). High-severity fires in dry sclerophyll forests result in gaps in canopy cover, encouraging shrub recruitment and reducing the vertical separation between shrubs and the canopy (Barker *et al.* 2022). This can last up to 30 years post-fire and increase the vertical fuel loads and flame heights of subsequent fire events (McCaw *et al.* 2008; Gould *et al.* 2011; Gordon *et al.* 2017; Barker *et al.* 2022). Eucalypts also produce highly volatile oils in their leaves, branches, bark and flowers (Guerrero *et al.* 2021, 2022) which can increase the amount of energy released during combustion (Younes *et al.* 2024). Terpenes found within the leaves of many eucalypt species have a low flammability limit (meaning that ignition can occur even at low concentrations in the air) and a low flash point (49°C), which further promotes fire spread and increases fire temperatures (Guerrero *et al.* 2021, 2022; Younes *et al.* 2024). Therefore, the increase in eucalypt species abundance is a possible cause for the rise in the frequency of high-intensity fire events over the past ~100 years observed in the CR-01 core.

A change in vegetation composition has also been observed in the Blue Mountains. Pollen records from the early to mid-Holocene suggest the reduced presence of *Eucalyptus* (Chalson and Martin 2009) with the vegetation of an open woodland or heath (Chalson and Martin 2009). Woody vegetation begins to increase in the Blue Mountains ~2000 cal year BP, with an increase in *Eucalyptus, Melaleuca* and Casuarinaceae (Chalson and Martin 2009). The past 100 years show a decline in Casuarinaceae with increased *Pinus*, *Kunzea, Baeckea* and *Leptospermum* (Black and Mooney 2006; Chalson and Martin 2009). Whilst many trends in vegetation change began before colonisation, it has been hypothesised that European activities encouraged the recruitment of woody taxa and altered fire regimes with higher fuel structures (Chalson and Martin 2009). The peak in aromatic/aliphatic ratio at the surface of the UBS-01 site, possibly corresponding to the 2019–20 bushfire, is up to 3× greater than fires recorded in 1882 (+84/−101) CE and 1737 (+157/−121) CE. This suggests that the expansion of eucalypts combined with the increased human occupation of the Blue Mountains could have resulted in more extreme fire conditions than previously experienced.

Altered vegetation composition in Namadgi and the Blue Mountains following colonisation agrees with existing studies that have found similar changes in Tasmania (Mariani *et al.* 2022). Coupled with the increased incidence of prolonged drought events (Palmer *et al.* 2023), this change in vegetation composition increases the landscape's ability to burn at high intensity.

Conclusion

Applying FTIR spectroscopy to sediment deposits from south-eastern Australia, we provide a ~3000-year record of fire history in the Blue Mountains and Namadgi National Parks. Both sites significantly extend the existing record of past high-intensity fire events by centuries to millennia, showing a dramatic increase in the frequency of high-intensity fires during the past ~200 years. From our results, we hypothesise that the fire regime in both Namadgi National Park and the Blue Mountains arises from the complex interactions between climate, people and vegetation, thus culminating in an increase in the frequency of extreme fire events. At both sites, this increase could be explained by a higher incidence of drought conditions that promote human and lightning ignitions. This, combined with increased woody taxa abundance, could promote more high-intensity fire events. The use of peak area ratios from the FTIR spectra provides an important development in our understanding of how fire intensity has changed in the recent past. This is of particular importance in these threatened ecological communities as high-intensity fire events have a greater impact on ecosystems, increasing the duration of time needed for recovery. For fire agencies, this information can inform future planning for management and fire-fighting efforts under more extreme fire conditions. Whilst additional sites are needed to assess Australia-wide trends, these results suggest that fire frequency and intensity may continue to rise in coming years as climate extremes continue to increase.

Supplementary material

Supplementary material is available online.

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