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European colonization and the emergence of novel fire regimes in southeast Australia

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Abstract

The rapid increase in severe wildfires in many parts of the world, especially in temperate systems, requires urgent attention to reduce fires' catastrophic impacts on human lives, livelihoods, health and economy. Of particular concern is southeast Australia, which harbours one of the most flammable vegetation types on Earth. While previous studies suggest climate and European activities drove changes in southeast Australian fire regimes in the last 200 years, no study has quantitatively tested the relative roles of these drivers. Here, we use a Generalized Linear Modelling to identify the major driver(s) of fire regime change in the southeast Australian mainland during and prior to European colonization. We use multiple charcoal and pollen records across the region and quantitatively compare fire history to records of climate and vegetation change. Results show low levels of biomass burned before colonization, when landscapes where under Indigenous management, even under variable climates. Biomass burned increased markedly due to vegetation/land-use change after colonization and a major decline in regional precipitation about 100 years later. We conclude that Indigenous-maintained open vegetation minimized the amount of biomass burned prior to colonization, while European-suppression of Indigenous land management has amplified biomass accumulation and fuel connectivity in southeast Australian forests since colonization. While climate change remains a major challenge for fire mitigation, implementation of a management approach similar to the pre-colonial period is suggested to ameliorate the risk of future catastrophic fires in the region.

Keywords

biomass, European colonization, fire, Indigenous, southeast Australia, vegetation

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Introduction

Catastrophic wildfires are becoming more frequent and severe in many parts of the world and are associated with unprecedented impacts (Bowman et al., 2017; Dutta et al., 2016; Filkov et al., 2020; Flannigan et al., 2013; Nauslar et al., 2018; Tran et al., 2020). This is particularly true in Australia and North America, as demonstrated by recent (2019/2020) catastrophic wildfires in southeast Australia and California (Bowman et al., 2017; CAL FIRE, 2020; Filkov et al., 2020). The 2019/2020 Black Summer wildfires in southeast Australia claimed 34 human lives, at least 2000 homes, 3 billion animals and 19 million hectares land area (Filkov et al., 2020). The fires have attracted growing concern internationally and locally in southeast Australia, which houses one of the most flammable vegetation types on Earth: dry sclerophyllous woodlands and forests (Bowman et al., 2017; Crisp et al., 2011; Dutta et al., 2016).

Fire regimes are complex and influenced by multiple factors, including vegetation type and moisture (Bradstock, 2010). Recent studies (Clarke et al., 2019; Tran et al., 2020) have shown that fire weather (dry, windy and hot days) significantly influences fire occurrence and is a significant predictor of the occurrence of catastrophic fires in southeast Australia. However, the role of factors associated with vegetation (fuel composition, connectivity and moisture) is not fully understood (Bradstock et al., 2020). Quantitative knowledge of long-term changes in vegetation composition and connectivity, as well as fire regimes, provide a robust baseline that can guide to effective fire management plans (Gillson et al., 2019). Palaeoecological records offer the possibility of undertaking such long-term quantitative studies, tapping into the rich knowledge archives of the past (Fordham et al., 2020).

Palaeoecological studies have shown that increasing climatic variability and anthropogenic land-use change drove centennial-scale shifts in fire activity (biomass burned) in southeast Australia for at least the last ~5000 years (Black et al., 2008; Kershaw et al., 2003; Mooney et al., 2011, 2012). On shorter timescales, agro-pastoral activities following Australia's colonization by Europeans in 1788 AD are thought to have contributed to landscape changes in the last 200 years, especially via the suppression of Indigenous land management, clearance of forests in some areas and promotion of wooded landscapes in others (Fletcher et al., 2021; Lunt et al., 2006). Several authors have sought to understand and quantify changes in fire activity in southeast Australia in the centuries before and after European colonization (e.g. Dodson and Mooney, 2002; Dodson et al., 1993, 1994a, 1994b, 1994c, 1995; Mooney et al., 2012). However, the drivers of past fire regimes in the region are still not fully understood, as no study has quantitatively tested the role of centennial-scale vegetation and climate changes in shaping fire regimes.

Here, we use a robust modelling approach to identify the major driver(s) of fire regimes in the southeast Australian mainland (SEAM) in the centuries before and after European initial colonization. To achieve this, we use multiple charcoal records from the SEAM, spanning the last 700 years, to reconstruct past biomass burned (an estimate of the amount of vegetation biomass consumed by landscape fire). This SEAM biomass-burned reconstruction was then quantitatively compared to records of vegetation turnover and independent multi-model-based records of past climate in the region. A quantitative estimate of rates of palynological change in pollen records was used to infer regional vegetation turnover (beta diversity), a reflection of vegetation (fuel) compositional change on the landscape. It has been empirically established that palynological rates of change in southeast Australian pollen assemblages are significantly correlated with vegetation compositional change in the region (Adeleye et al., 2021b). The results from this study will help inform management efforts not only in Australia, but also in other fire-prone regions globally.

Study area

Wildfire seasons vary across Australia, generally ranging from winter-dominated, frequent, low-intensity in northern regions characterized by a monsoon climate, to summer-dominated, infrequent high-intensity in southern regions characterized by a temperate climate (Archibald et al., 2013; Miller and Murphy, 2017). In southeast Australian sclerophyll forests, intense fires primarily occur during late summer–autumn (Australian Bureau of Meteorology, 2021).

The SEAM climate is mainly modulated by El Niño Southern-Oscillation (ENSO), Indian Ocean Dipole (IOD) and the Southern Westerly Winds (SWW; CSIRO, 2012). ENSO and IOD bring drought to the region, especially in El Niño years, which are associated with extreme fire weather and fire events (Abram et al., 2020; Mariani et al., 2016). SWW have the greatest influence in the southernmost part of the SEAM. Positive phases of SWW are generally associated with high summer rainfall (low winter rainfall), while negative phases are associated with high winter rainfall (low summer rainfall; Australian Bureau of Meteorology, 2021). Vegetation on the SEAM is dominated by *Eucalyptus* forests and woodlands, as well as sclerophyllous shrublands (Department of the Environment and Water Resources, 2007), and many lowland areas have been cleared for farmland (Department of Agriculture, Land and Environment, 2018a; Figure 1).

Methods

Sedimentary charcoal is the most robust indicator of past fire regimes in a given landscape, containing information on past biomass burned and burning frequency (Ali et al., 2012; Whitlock and Larsen, 2001). Sixty-one charcoal records with at least one radiocarbon date every 3000 years were selected across the SEAM from the Global Paleofire database (https://www.paleofire.org/; see Table 1 in Supplemental Material for charcoal data information). Composite charcoal *z*-scores were then calculated at 50-year resolution using the 'palaeofire' ('pfComposite') package in 'R' (Blarquez et al., 2014; R Core Team, 2020) to reconstruct regional biomass burned in the last ~700 years. A Kruskal-Wallis ANOVA test was also performed using the 'palaeofire' package in 'R' to test the dissimilarity in biomass burned between different time periods (150-year time bin; Blarquez et al., 2014; R Core Team, 2020).

To reconstruct regional vegetation turnover, nine pollen records spanning the last ~700 years with at least 100-year sampling resolution and at least one radiocarbon/^{210}Pb date every 400 years were obtained from a southeast Australian database (Herbert and Harrison, 2016). Pollen records with centennial-scale resolution were required for this study and only nine records met this criterion in the SEAM region (see Table 2 in Supplemental Material for pollen data information). Pollen records were divided into 100-year time bins and Squared Chord Distances (SCD) calculated between randomly selected samples (resampled 50×) from adjacent bins to estimate temporal vegetation turnover, using the 'analogue' package in 'R' (R Core Team, 2020; Simpson and Oksanen, 2020). The average SCD of all nine pollen records was then taken, representing regional vegetation turnover for the SEAM (Adeleye et al., 2021b).

Published pollen and charcoal record chronologies were accepted. Recalibration of published dates using the latest radiocarbon calibration curve (SHCal20: Hogg et al., 2020) made no difference – all published calibrations overlapped with recalibrations at 68% and 95% confidence intervals. Exotic pollen, such as *Pinus*, was also commonly used as a biostratigraphic marker to fine-tune the timing of European settlement in the records (e.g. Black and Mooney, 2006; Dodson et al., 1994b; Dodson, 1974; Kodela and Dodson, 1988; Mooney et al., 2007).

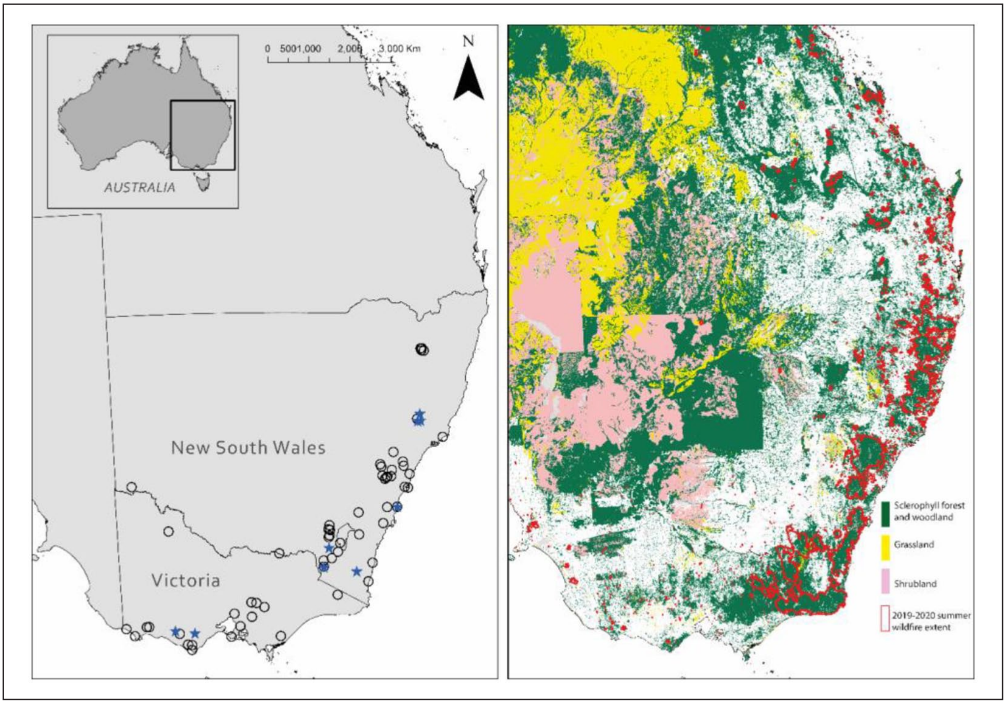

Figure 1. Locations of charcoal (black hollow circles) and pollen records (blue stars) on the southeast Australian mainland used in this study (left panel). Present vegetation distribution and extent of 2019–2020 summer wildfires (right panel). White-coloured areas on the right panel represent cleared areas. (Department of Agriculture, Land and Environment, 2020 – National Indicative Aggregated Fire Extent Datasets; Department of Agriculture, Land and Environment, 2018b – National Vegetation Information System version 5.1).

Generalized linear modelling (GLM) with Gaussian distribution was used to identify major drivers of biomass burned, with vegetation turnover and climatic drivers as predictors. The effect of temporal autocorrelation was removed from the model by multiple resampling of each variable at a lower resolution 1000× (Mellin et al., 2010). The best model was selected based on the corrected Akaike's information criterion (AICc) and delta AICc (dAICc) statistics. The climate records used are multi-model averages of ENSO (Nino 3.4 index), temperature and precipitation simulations for eastern Australia based on simulations of the last millennium from a set of climate models: BCC-CSM1.1, CCSM4, CSIRO-Mk3L-1-2, GISS-E2-R, IPSL-CM5A-LR and MPI-ESM-P (see Brown et al., 2016; Schmidt et al., 2012 for climate model details). Alongside the fact that these model-based climate simulations were developed for eastern Australia, the simulations were selected due to the model robustness and their high temporal resolution.

Results

Charcoal composite and vegetation turnover results show relatively low biomass burned (z-score < 0), with minimal vegetation turnover (SCD < 0.2) before 1788 AD, while biomass burned (z-score > 0) and vegetation turnover (SCD > 0.2) increased markedly after this time, especially since 1850 AD (Figure 2). The charcoal composite using a subset (n = 17) of the charcoal

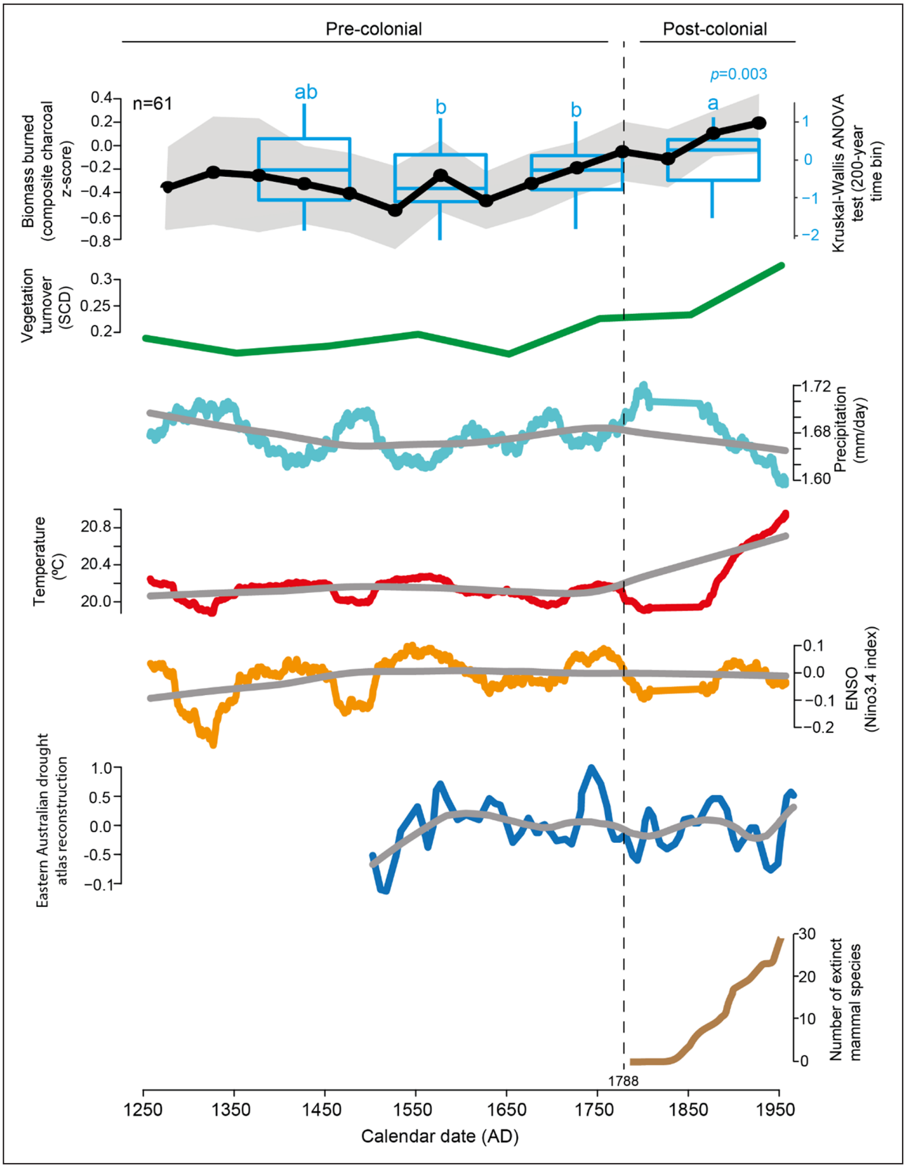

Figure 2. Biomass burned in southeast Australia over the last 700 years before present (present = 1950) with error estimates (grey-shaded area) in relation to vegetation turnover, precipitation, temperature and ENSO, with loess smoothing (grey curves, span = 0.5). Boxplots are the Kruskal-Wallis ANOVA test results, which indicate a significant ($p < 0.05$) difference between biomass burned before and after European colonization. ENSO (Nino 3.4 index), temperature (°C) and precipitation (mm/day) are based on simulations of the last millennium from a set of climate models for eastern Australia: BCC-CSM1.1, CCSM4, CSIRO-Mk3L-1-2, GISS-E2-R, IPSL-CM5A-LR and MPI-ESM-P (Brown et al., 2016). Vegetation turnover (SCD) is based on nine pollen records (Herbert and Harrison, 2016) and biomass burned (charcoal *z*-score) estimate is based on composite of 61 charcoal records from the southeast Australian mainland (Global Paleofire Database – https://www.paleofire.org/). See Tables 1 and 2 in Supplemental Material for pollen and charcoal data information. Also shown is eastern Australian drought atlas reconstruction, with loess smoothing (span = 0.25), which is based on tree rings and coral series (Palmer et al., 2015), as well as the number of extinct mammals in Australia since European colonization (Woinarski et al., 2015).

Table 1. GLMs comparing biomass burned (BB) to vegetation turnover (SCD), temperature (temp), ENSO and precipitation (precip).

Model	AICc	dAICc	Rm	% Deviance
BB = Veg + Precip	−38.1218	0	84.35	91.7
BB = Veg + Precip + Temp	−36.8575	1.264	85.93	91.8
BB = Veg + ENSO + Precip	−34.8237	3.298	84.5	90.3
BB = Veg + ENSO	−34.1719	3.95	81.11	90.2
BB = Veg + Temp	−33.6057	4.516	80.59	94.3
BB = Veg + ENSO + Temp + Precip	−32.8776	5.244	85.94	89.9
BB = Veg + ENSO + Temp	−31.8366	6.285	82.13	95.8
BB = Temp + Precip	−25.3593	12.762	71.25	83
BB = ENSO + Temp + Precip	−24.1344	13.987	74.21	85.7
BB = ENSO + Temp	−7.26838	30.853	31.97	58.4
Null	−5.01251	33.109	0	
BB = ENSO + Precip	0.502465	38.624	1.5	41.9

Models are ranked based on Akaike's information criterion corrected for small sample sizes (AICc) and delta AICc. Also shown are percentage of deviance explained and marginal R^2 (Rm). The best model (top) is one with the lowest AICc and dAICc values, which in this case is 'BB = Veg + Precip'.

records with at least one radiocarbon date per 700 years shows a similar trend in biomass burned ($r = 0.8$, $p = 0.002$). Kruskal-Wallis ANOVA test shows a significant ($p < 0.05$) deference between biomass burned before and after 1788 AD (Figure 2). Generalized linear models (GLMs) show a combination of vegetation turnover and precipitation changes best explain regional biomass burned, judged by the low AICc and dAICc values (Table 1).

Discussion

Potential sources of error

The charcoal and pollen records used in this study are currently the best publicly accessible data sets for the SEAM spanning the time frame considered in this study. We acknowledge that the quality of these data sets (e.g. Black and Mooney, 2006; Dodson et al., 1994b, 1994d; Kodela and Dodson, 1988; Mooney et al., 2007), especially in terms of the generally low resolution and poor chronological control over the targetted time period, may have potentially influenced the timing of shifts in our vegetation turnover and biomass burned reconstructions. Hence, given chronological uncertainties, dates given in the text should be regarded as approximations. Though the overall number of charcoal data sets analysed is high ($n = 61$), the majority of the records are non-contiguous microscopic (<125 µm) charcoal records, which have the potential of missing fire events. Despite these limitations, the result presented in this study provides a quantitative insight into the drivers of fire regimes in pre-colonial and colonial landscapes of the SEAM.

Fire regime change driven by vegetation and precipitation changes in southeast Australia

In both Northern and Southern Hemisphere temperate ecosystems, palynological rates-of-change estimates with SCDs >0.2 indicate complete turnover in vegetation types across space and through time (Adeleye et al., 2021b; Overpeck et al., 1985). Our results (Figure 2) indicate that prior to the

18th century, vegetation was relatively stable and after that time major turnover occurred. Our generalized linear models (GLMs) show that a combination of vegetation turnover and precipitation changes best explain regional biomass burned on the SEAM in the last ~700 years (Table 1).

Vegetation type/structure and moisture, as well as temperature, are major determinants of fire regime (Cochrane, 2009; Daniau et al., 2012). However, vegetation type/structure and moisture are more important in dry vegetation types, where fire is often limited by biomass fuel loads and connectivity (Bradstock, 2010; Cochrane, 2009; Daniau et al., 2012; Pausas and Paula, 2012). High fuel connectivity in dry woody vegetation is a function of biomass accumulation (increased vegetation growth), which can be caused by one or more of the following: (1) high moisture, (2) high CO_2 and (3) insufficient disturbance, such as infrequent fires (Murphy et al., 2014; Pausas and Paula, 2012). A large percentage of the SEAM's forest vegetation falls into the category of dry, contiguous, woody vegetation, making the region one of the most fire-prone places on Earth (Keith, 2017). Also, compared to the pre-colonial landscape, present-day forests on the SEAM are denser and have greater fuel connectivity, while present-day open vegetation has much less tree cover (Mariani et al., in press).

Indigenous population growth and land usage were high and widespread across the SEAM during the last millennium, especially prior to European colonization in 1788 AD (Williams, 2013; Williams et al., 2015). Scientific studies and ethnographic accounts indicate that Indigenous people regularly and deliberately burned vegetation to keep landscapes open in order to promote resource availability, such as diverse plant-based food and herbivore grazing for hunting, as well as to increase land accessibility and freshwater resources (Bliege Bird et al., 2020; Bowman, 1998; Gammage, 2005, 2008, 2012; McWethy et al., 2017; Mulvaney and Golson, 1971). Other fire-related activities carried out by Indigenous people in the past include cooking, ceremonies and rituals (Mulvaney and Golson, 1971). Existing pollen records suggest European land-use transformations drove tree-cover declines in the partially wooded landscapes on the SEAM following initial colonization (Dodson et al., 1994a, 1994b, 1994c, 1995). A recent land cover reconstruction suggests that forest/woodland understorey shrub density likely increased after colonization at the same time as agro-pastoral landscapes were expanding (Mariani et al., in press). These denser forest understoreys might represent a major increase in forest connectivity over the last two centuries.

Vegetation turnover recorded from 1788 AD (especially since 1850 AD) on the SEAM likely reflects this polarization in fuel connectivity and woody biomass accumulation following European arrival, which in turn led to increased biomass burned across the landscape. The majority (90%) of pollen records considered in our study show increases in shrubs such as Kunzea, Ericaceae, Melaleuca and Leptospermum after 1788 AD. Shrub expansion would have increased fuel connectivity by creating ladder fuels linking the surface vegetation layer to the tree canopy (Sullivan et al., 2012), facilitating widespread and severe fires and increases in the amount of biomass burned on the landscape. Indigenous peoples used frequent low-intensity fires (cool burning) to promote mosaic landscapes, thus reducing fuel connectivity and fire spread (Bowman, 1998; Gott, 2005). Our data support the hypothesis that European suppression of Indigenous cultural burning helped to drive increases in vegetation thickening (biomass accumulation and fuel connectivity) on the SEAM (Bradstock et al., 2002; Mariani et al., in press).

A two-way feedback exists between fire and vegetation, such that fire can drive vegetation turnover and vice versa (Feurdean et al., 2020; Marlon et al., 2016). However, fire regimes in most cases are pre-conditioned by vegetation structure and moisture, especially in temperate ecosystems (Bradstock, 2010; Feurdean et al., 2020; Pausas and Paula, 2012). A study of contemporary fire ecology in temperate southeast Australia (Bradstock, 2010) shows that biomass availability (vegetation) is the major factor limiting fire activity. Deliberate reduction of biomass load (to limit fuel connectivity) has been proposed to reduce potential risks of fire weather-driven catastrophic fires in the region (Matthews et al., 2012).

At a regional scale, decreasing precipitation and drought variability are associated with the Interdecadal Pacific Oscillation across eastern Australia since the 1600s (Gergis et al., 2012; Mantua and Hare, 2002; Palmer et al., 2015). This climatic trend is likely to have not only influenced biomass burned as early as ~1650 AD, but also exacerbated biomass burned over the last 200 years by increasing fuel dryness. The unstable/weak connection between ENSO (Nino3.4) and precipitation across eastern Australia on a decadal scale (Brown et al., 2016; Palmer et al., 2015) may explain why our GLMs identified ENSO as a minor driver of fire regimes in southeast Australia over the last ~700 years.

Precipitation was also generally low between ~1450 and 1650 AD, a possible indication of pre-existing climate variability prior to European colonization in 1788 AD (Barr et al., 2014; Figure 2). However, in contrast to the colonial period, biomass burned during this period was relatively low, and may be explained by the open vegetation maintained by Indigenous peoples through frequent low-intensity patch burning (cool burning), which reduced understorey shrub load and fuel connectivity for landscape-scale fires (Gammage, 2005). Other ecological factors, such as herbivory and changes in soil conditions may have also played a role in maintaining relatively low levels of plant biomass and vegetation density (Eldridge et al., 2017), contributing to the open landscape and low biomass burned during this period. Native mammal populations have crashed in Australia since the 1850s (Woinarski et al., 2015), but prior to this time these herbivores are likely to have played a key role in suppressing biomass (Figure 2).

Overall, the role of Indigenous people in maintaining diverse and interconnected ecosystems and landscapes appears to have been dismissed or even deliberately suppressed since European colonization (Fletcher et al., 2021; Gammage, 2012). The disruption of Indigenous burning practices has not only elevated the present-day risk of catastrophic fires in southeast Australia but has also led to changes in biodiversity maintained by Indigenous skilful burning for many millennia (Adeleye et al., 2021a, 2021b; Bowman, 1998; Bowman et al., 2011). While climate-change risks remain the primary global challenge for fire mitigation, local-scale management targetted at restoring pre-colonial fire regimes will likely help reduce present fuel connectivity, thus altering fire behaviour and diminishing the potential for widespread wildfires in SEAM forests and woodlands. This conclusion echoes the recommendations of the Australian Royal Commission into Natural Disaster Arrangements on wildfire, which highlighted the urgent need for states and territories to strengthen their engagements with Traditional Owners to further explore Indigenous land and fire management insights throughout the process of public management activities (Royal Commission into Natural Disaster Arrangement, 2020).

Management approaches that draw on traditional knowledge are also now being recommended in South America, North America and southern Europe to reduce risks and effects of severe wildfires in fire-prone ecosystems (Eloy et al., 2019; Fernandes et al., 2013; Keane et al., 2002; Mistry et al., 2019; White et al., 2011). It is therefore becoming apparent that the knowledge of the past (traditional land management) is key to effective future management of severe wildfires globally. The earlier this is embraced by land managers and policy makers, the lesser the risk of future losses of human lives, properties, cultural heritage, ecosystem functions and biodiversity associated with severe wildfires (CAL FIRE, 2020; Filkov et al., 2020; Tran et al., 2020).

Conclusion

Results from this study support the idea that Indigenous peoples maintained a fire regime with low levels of biomass burning on the southeast Australian mainland prior to European colonization, while European suppression of Indigenous cultural land management, exacerbated by increasingly dry conditions, has driven an increase in biomass burned after colonization. Considering the projected increase in fire weather and extreme fire events for southeast Australia, exploring management approaches modelled on Indigenous cultural burning practices is recommended to reduce the risks of future catastrophic wildfires in the region.

Authors' note

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Supplemental material

Supplemental material for this article is available online.

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