Disruption of cultural burning promotes shrub encroachment and unprecedented wildfires

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Recent catastrophic fires in Australia and North America have raised broad-scale questions about how the cessation of Indigenous burning practices has impacted fuel accumulation and structure. For sustainable coexistence with fire, a better understanding of the ancient nexus between humans and flammable landscapes is needed. We used novel palaeoecological modeling and charcoal compilations to reassess evidence for changes in land cover and fire activity, focusing on southeast Australia before and after British colonization. Here, we provide what we believe is the first quantitative evidence that the region's forests and woodlands contained fewer shrubs and more grass before colonization. Changes in vegetation, fuel structures, and connectivity followed different trajectories in different vegetation types. The pattern is best explained by the disruption of Indigenous vegetation management caused by European settlement. Combined with climate-change impacts on fire weather and drought, the widespread absence of Indigenous fire management practices likely preconditioned fire-prone regions for wildfires of unprecedented extent.

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The impact of large wildfires is escalating across many parts of the globe as climatic conditions become more conducive to extreme fire weather (Nolan *et al*. 2020). Western North America and southeast Australia are global hotspots of catastrophic wildfires with severe economic and social consequences (Bowman *et al*. 2017). As human populations increase worldwide, urban expansion into forested zones and climate change are raising fire impacts to unprecedented levels (Bowman *et al*. 2017). Thus, the development of efficient forest management plans in accordance with past land-use history is imperative (Whitlock *et al*. 2018).

In a nutshell:

- Historically unprecedented fires in Australia have raised questions about fire management and changes in forest structure since British colonization
- New modeling techniques were used to assess past vegetation change from fossil pollen sequences
- Results show an increase in shrub cover in southeast Australian woodlands following colonial settlement, linked to the suppression of Indigenous burning practices
- Increased shrubbiness, in conjunction with climate change, may have exacerbated wildfires in southeast Australian forests

Western North America and southeast Australia are areas where European colonization disrupted long-standing Indigenous burning practices (Guiterman *et al*. 2019; Fletcher *et al*. 2021). In North America, tree-ring evidence indicates the suppression of Indigenous fire regimes, or "cultural burning", had major consequences for forest composition and fuel connectivity (Whitehair *et al*. 2018; Guiterman *et al*. 2019; Larson *et al*. 2020). Ecologically sustainable Indigenous fire management protected biodiversity and provided ecosystem services for millennia. Cessation of these practices has increased the risk of environmentally and socially destructive extreme fires (Whitehair *et al*. 2018).

Indigenous peoples have inhabited Australia for at least 65,000 years (Clarkson *et al*. 2017) and oral tradition, historical, and ethnographic sources attest to sophisticated systems of land management, including skillful cultural burning (Gott 2005; Gammage 2011; Pascoe 2014). Routinely ignoring these sources, authorities in colonial and subsequent governments falsely asserted Australia as *terra nullius* ("nobody's land"), thereby justifying land expropriation and discounting the wisdom of traditional ecological knowledge (Borch 2001; Steffensen 2020).

Prior to British colonization in the year 1788, Australia's flammable vegetation had been managed by Indigenous

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peoples primarily through the frequent ignition of small fires (Gott 2005). A consistent ecological outcome of this management was to alter the balance between herbaceous and woody biomass, limiting shrub density in understory vegetation and maintaining patchy open woodlands and savanna-like landscapes across a broad elevational range (Gott 2005; Gammage 2011). Not only did fire management increase landscape productivity and facilitate hunting practices, it was a tangible cultural connection of people to place (Jones 1969; Hallam 2014). Indigenous fire regimes created fine-scale landscape heterogeneity (Bliege Bird *et al.* 2016), with pyrodiverse mosaics of open woody vegetation (ie low shrub abundance) and sparsely treed plains (Bowman and Prior 2004) that were less prone to destructive fires than current forests (Gott 2005). In contrast, colonial vegetation management implied clear-cutting and intense firing to create large-scale patches in areas deemed suitable for agricultural activities, particularly low-elevation plains, while forests in rugged terrain were left unmanaged or exploited through selective logging (Griffiths 2001).

Globally, there is growing recognition that Indigenous burning practices are key to sustainable fire management (Colombaroli *et al.* 2019). In Australia, cultural burning is experiencing a renaissance (Steffensen 2020), yet its potential to mitigate catastrophic forest fires is still under debate (Cary *et al.* 2003; Russell-Smith *et al.* 2009). In part, this discussion stems from uncertainties concerning how British colonization affected the composition and structure of vegetation, thereby altering the core components of fire regimes (frequency, extent, and severity) (Head 1989; Bradstock *et al.* 2002; Enright and Thomas 2008). Accurate determination of pre-colonization baselines, along with an understanding of vegetation and fire-regime trajectories, are prerequisites for the development of sustainable fire management.

Proxies for Indigenous-managed landscapes

Science has had mixed success in uncovering evidence of cultural burning on different continents. Detailed fire-scar studies – crucial for demonstrating the prevalence of Indigenous cultural burning and the impacts of its cessation in North America (Whitehair *et al.* 2018; Guiterman *et al.* 2019; Larson *et al.* 2020) – cannot be replicated in southeast Australia. Detailed fire-scar histories are prevented by the poor dendroecological potential of *Eucalyptus* to disclose annual fire history (Brookhouse 2006), and the loss of ancient trees to logging, land-use change, and recent severe fires in southeast Australia (Cary and Banks 2000). This necessitates an alternative approach to investigating how cessation of Indigenous land management practices, due to forced removal from traditional lands and imposition of foreign fire management practices, changed the region's forest structure.

Pollen sequences are commonly used to reconstruct past vegetation structure on local to regional scales (Birks and Berglund 2017). Pollen data carry numerous biases, the most important of which is pollen productivity. Novel modeling techniques, such as the Regional Vegetation Abundance from Large Sites (REVEALS) model, overcome these biases (Sugita 2007). Application of REVEALS shows that classical pollen-based studies greatly underestimate the extent of past cultural landscapes (Gaillard *et al.* 2010) and the extent to which anthropogenic fire has shaped past vegetation (Vannière *et al.* 2016; Roos *et al.* 2019); this approach holds great potential for reconstructing cultural landscapes in Australia (Mariani *et al.* 2017).

Controls on fire in southeast Australian vegetation

On a landscape scale, fire occurrence and spread are determined by the confluence of an ignition source (humans or lightning), sufficient fuel (biomass), and suitable weather (Krawchuk *et al.* 2009). Ignition sources in southeast Australia have been largely anthropogenic since the arrival of Indigenous peoples (Bradstock *et al.* 2002). Although lightning-strike fires are still relatively rare, these have increased in recent decades as a result of climate change (Styger *et al.* 2018).

Biomass availability depends on long-term moisture availability and landscape management (decades to millennia), while its suitability to burn depends on short-term weather conditions (hours to months) (Bowman *et al.* 2009). The sclerophyll vegetation of southeast Australia characterizes one of the most fire-prone regions on Earth (Hennessy *et al.* 2005). In this region, fires range from infrequent and low-intensity in pasture/cropland, through medium frequency and variable intensity in dry sclerophyll forests and woodlands with limited tree mortality, to infrequent but high intensity in wet sclerophyll forests, often with substantial tree mortality (Bradstock 2010; Murphy *et al.* 2013).

Fire weather (hot, dry, and windy conditions) in southeast Australia is regionally controlled by interactions among the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Southern Annular Mode (SAM) (Hennessy *et al.* 2005; Harris and Lucas 2019). These inter-annual climatic modes have played major roles in modulating rainfall patterns and preconditioning vegetation to burn across southeast Australia over the past 50 years (Harris and Lucas 2019). Climatic change over the past 1000 years has been reconstructed using corals, tree rings, and speleothems (for temperature; Gergis *et al.* 2016), as well as a seasonal sea-salt record from Antarctica (for precipitation; Vance *et al.* 2015). These records show that the most substantial climatic change over the past millennium occurred in the mid- to late-20th century through increased temperature and greater frequency of mega-droughts, both of which are linked to anthropogenic climate change.

Research questions and hypotheses

Historical sources from early colonial times suggest that Aboriginal burning maintained vast expanses of grassy woodlands across southeast Australia (see Gammage [2011] and references therein). In contrast, interpretations of unmodeled pollen records extracted from lake and wetland sediments suggest greater forest cover during the pre-colonial period (WebTable 1). The extent to which suppression of cultural burning since 1788 triggered broad-scale changes in forest/woodland distribution, fuel loads, and plant community structure remains unclear (Nolan *et al*. 2020). To accurately quantify how vegetation changed between pre-colonial and post-colonial times, we applied the pollen-based REVEALS model to southeast Australia for the first time. Our primary objective was to address two research questions: (1) was there an observable change in the composition and structure of vegetation after British colonization compared to pre-1788 baselines, and (2) was there an increase in the amount of biomass burned over the same period?

We hypothesized that alterations in fire patterns and land management better account for changes in vegetation structure (thinning versus thickening) across southeast Australia than does a purely climatic explanation. We would expect that the disruption of Indigenous management and imposition of British-inspired management led to woody thickening (specifically, expansion of the shrub layer) and a reduction in grass cover in forest/woodland areas. Consequently, this shrub encroachment might have exacerbated wildfires under the compounding influences of climate change. Furthermore, we expected that land clearing contributed to declining woody biomass in areas targeted for agro-pastoral activities. If climate change were the sole driver of post-colonial vegetation change and biomass burning, we would expect to see evidence of a relatively consistent regional pattern across different land-use zones.

Methods

We applied REVEALS (Sugita 2007) to quantify past vegetation using 52 pollen records in southeast Australia over the past 1000 years (WebPanel 1; WebTable 1; WebFigure 1). The REVEALS model was run to convert raw pollen data into estimates of land cover by correcting for biases in pollen production (ie different plant species produce different amounts of pollen) and pollen dispersal (ie dispersal patterns differ in response to pollen grain properties) (Sugita 2007). Relative pollen productivity estimates (RPPEs) required for REVEALS were produced for the 19 most abundant pollen taxa regionally (see WebPanel 1 for extended methodology; WebTables 1–3). REVEALS was executed using the R package *disqover* (Theuerkauf *et al*. 2016; R Core Team 2020), along with a Lagrangian stochastic model (LSM) for pollen dispersal (Theuerkauf *et al*. 2013; Mariani *et al*. 2016, 2017). RPPEs were validated using modern-day pollen data from an independent set of lake sediment samples and modern-day plant cover data (WebPanel 1). To reconstruct past vegetation structure, we grouped the 19 modeled taxa into three main structural groups: trees (TR), shrubs/heaths (SH), and herbs/grasses/sedges (HG) (Figure 1).

Alongside land-cover change, we reconstructed past fire activity from 109 existing sedimentary charcoal records (WebTable 1c), providing a proxy for "biomass burned" across the landscape (Ali *et al*. 2012). Fire regimes have various components (eg frequency, severity). Of these, "biomass burned" is the only component of past fire regimes that can be reliably reconstructed from available data covering southeast Australia.

We compared two time slices, pre-colonial (1000–1788 CE) and post-colonial (1788 CE–present), estimated on the basis of radiometric dating, with exotic *Pinus* pollen for additional chronological support. Samples in the pollen database have a median temporal resolution of 138 years over the pre-colonial period and 48 years over the post-colonial period. We used the date of initial British colonization (1788 CE) as a conservative reference point, recognizing that the colonization frontier was mobile in space and time after this date. The dataset was too limited in its temporal resolution to track the timing of colonization frontiers. The multisite REVEALS model does not permit local-scale assessment of land-cover change (Sugita 2007). However, we distinguished two groups of sites based on their current vegetation (open versus forest/woodland) to unpack trajectories of change in major ecosystems.

Results

The modern pollen–vegetation calibration conducted in this study was found to correct for differing pollen production among Australian plants (Figure 1) and to be robust to validation (WebFigure 3). When applied to pre- and post-colonization pollen data, the model shows that grass and herb communities dominated the pre-colonial period, especially on mainland Australia (Figure 2). On average, grass and herb cover accounted for ~51% of the vegetation composition across all sites, whereas regional tree cover as well as shrubs and heaths covered ~15% and ~34% of the landscape, respectively. These results contrast starkly with traditional pollen reconstructions that emphasize the extent of pre-colonial forest and woodland cover (WebTable 1b), with estimates of 35% herbs and grasses, 48% trees, and 17% shrubs (expressed as pollen percentages).

Comparisons between pre- and post-colonial vegetation (Figures 2 and 3) display site-by-site trajectories, highlighting localized patterns of land-cover change (Figure 3; WebFigure 4). Sites currently located within forest/woodland vegetation had reduced shrub cover in pre-colonial times and became shrub-rich during the post-colonial period (green arrow in Figure 2a; Figure 3c). Before colonial settlement, sites currently within open landscapes were already dominated by grassy/herbaceous vegetation, often constituting >90% land cover. However, open-vegetation areas had slightly greater tree cover during

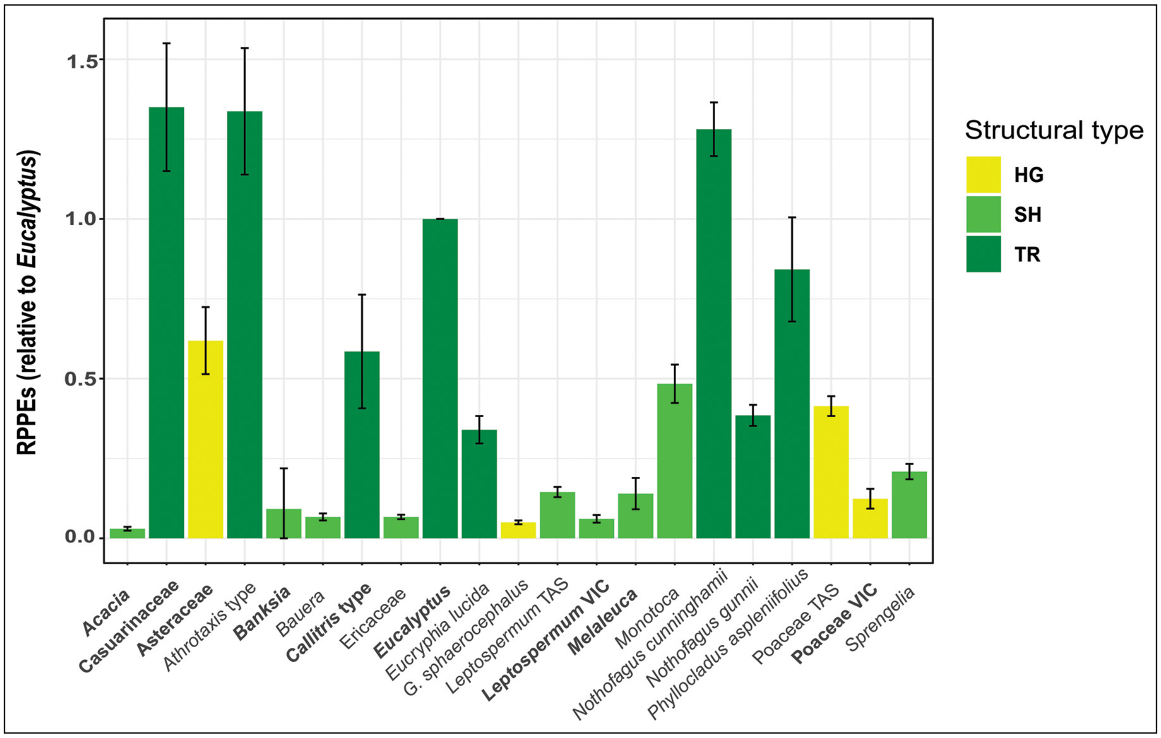

Figure 1. Relative pollen productivity estimates (RPPEs [relative to Eucalyptus]) used in this study for Regional Vegetation Abundance from Large Sites (REVEALS) modeling. RPPEs calculated for taxa included within this work are designated in bold font along the x axis; the remainder were previously published in Mariani *et al.* (2016). HG = herbs/grasses/sedges, SH = shrubs/heaths, TR = trees. TAS and VIC refer to the Australian states of Tasmania and Victoria, respectively. Error bars indicate the standard error of RPPEs.

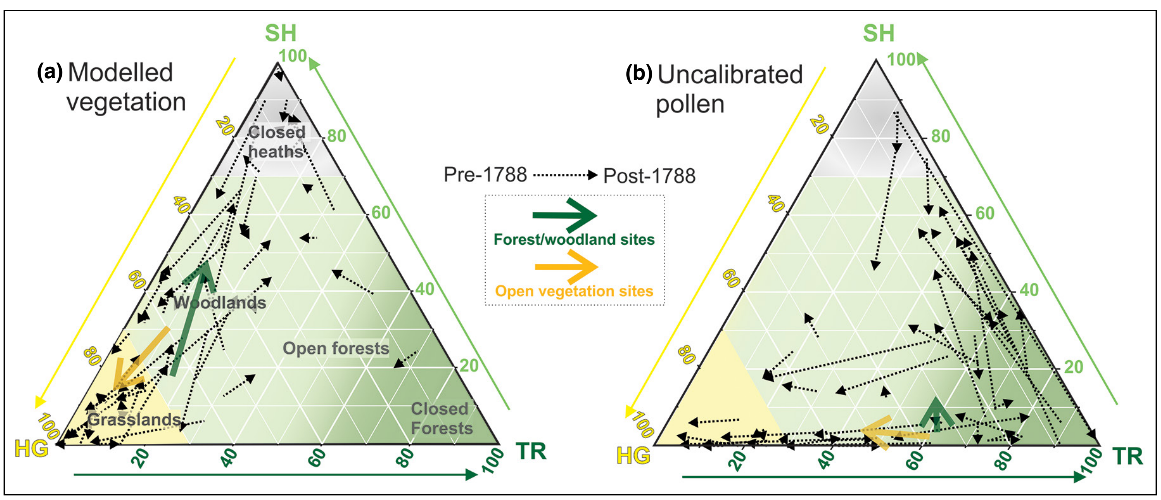

Figure 2. Pre- to post-colonial land-cover change at 52 sites in southeast Australia. Black arrows represent trajectories of individual sites; arrows point toward post-1788 data points. (a) Ternary diagram showing trajectories of change from pre- to post-colonial modeled land cover using REVEALS for 52 sites across southeast Australia. (b) Ternary diagram showing trajectories from pre- to post-colonial uncalibrated pollen percentages. Thick arrows represent median land cover trajectories within present-day forest/woodland (green) and open vegetation (yellow) sites. The broad vegetation classification by structural type and canopy cover follows Hnatiuk *et al.* (2009). The two-letter abbreviations HG, SH, and TR are the same as those defined in Figure 1.

pre-colonial times, which declined post-1788 as grass cover expanded (yellow arrow in Figure 2a; Figure 3a).

Charcoal results indicated that pre-colonial biomass burned was similar across all land-use types, and exhibited marked continuity through space and time (Figure 4; WebFigure 5), with less biomass burned in currently open vegetation (Figure 4). Biomass burned during the post-colonial period was higher in both land-use types (forest/woodland sites as well as open vegetation sites; Figure 4) and highly variable (WebFigure 5b).

Discussion

Pre-colonial cultural landscapes of southeast Australia

Integration of land-cover reconstructions and fire history provides empirical evidence that the landscapes observed by early British colonists were the result of human management, with frequent, landscape-wide use of fire (cultural burning) by Indigenous peoples (Figures 2–4). Our reconstruction of southeast Australian vegetation is – to the best of our knowledge – the first regional quantification of pre-colonial land-cover patterns in Australia, and indicates that these landscapes were predominantly grassy, with low tree cover (Figures 2 and 3). Although in disagreement with previous interpretations based on unmodeled pollen results (Figure 1b; WebTable 1b), our results match the body of knowledge about landscapes and landscape management held by Indigenous Australians while also corroborating historical records, including the diaries and artworks of early European settlers, who depicted much of the southeast Australian landscape as largely open and grassy, with scattered trees and shrubs (see Gammage [2011] and references therein). Modeling results suggest low tree cover at the regional scale (10^4–10^5 km^2), consistent with a savanna-like environment. The model was unable to reconstruct the spatial mosaic of the landscape, however, and therefore dense, small-scale forest patches and clearings likely existed within the regional matrix of open woodland.

We acknowledge that the transition from Indigenous management to British occupation was uneven temporally and spatially, and was almost certainly affected by varying levels of land clearing, soil degradation, and livestock grazing (Head 1989). For instance, the largest reduction in tree and shrub cover occurred in areas that are currently characterized by open vegetation, especially in flat and low-elevation regions with fertile soils (such as the plains of western Victoria) that were targeted and cleared for agriculture and livestock grazing (Figures 3 and 4). In contrast, in regions of poor agricultural potential (eg steep coastal areas), the disruption of Aboriginal fire management led to an increase in the density of shrub and heath cover in forests and woodlands (Figures 3 and 5). These trends confirm the view that southeast Australian forests have experienced substantial shrub encroachment since the time of initial British colonization (Bradstock *et al.* 2002).

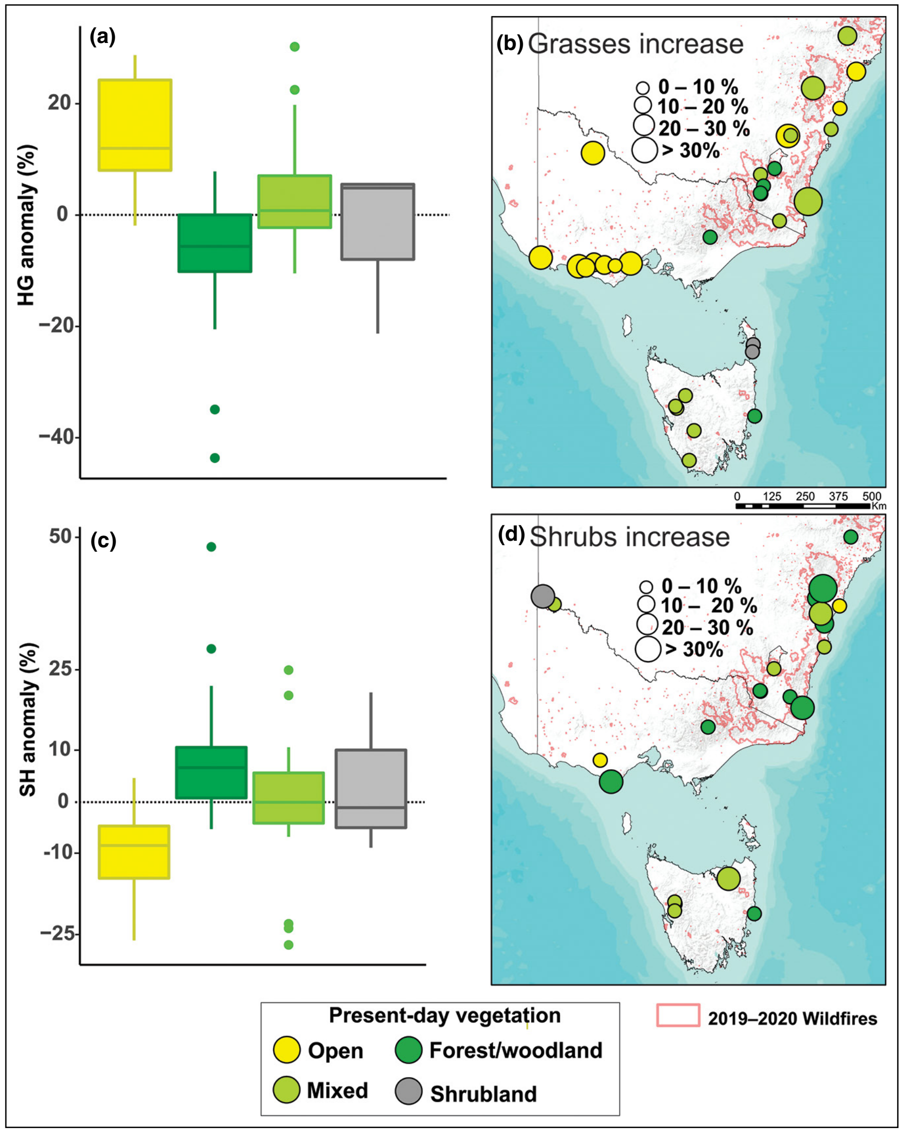

Figure 3. Summary of land-cover modeling results. On the left side are boxplots showing (a) HG and (c) SH land-cover anomalies (% change from pre- to post-colonial period). Horizontal lines within boxes depict median values, boxes represent the interquartile range (25th–75th percentiles), whiskers (vertical lines) represent the full range of values (below the 25th quartile and above the 75th quartile), and solid circles depict outliers. The two-letter abbreviations HG and SH are the same as those defined in Figure 1. On the right side are maps displaying sites that underwent increases in (b) HG and (d) SH, differentiated by present-day surrounding vegetation. Sites with negative anomalies are not included in the maps. Open vegetation (n = 12), forest/woodland (n = 17), mixed vegetation (n = 20), shrubland (n = 3).

Biomass burning trends across southeast Australia

Long-term fire history reconstructions demonstrate that fire has long been present in the Australian landscape, and was deeply intertwined with climatic change and Indigenous cultural practices (Kershaw *et al.* 2002; Mooney *et al.* 2011). The consistent occurrence of charcoal in sediments prior to 1788 (WebFigure 5; Mooney *et al.* 2011) proves that fire was an almost universal feature of the southeast Australian landscape. Pre-colonial fire regimes were remarkably stable over time in open and woodland/

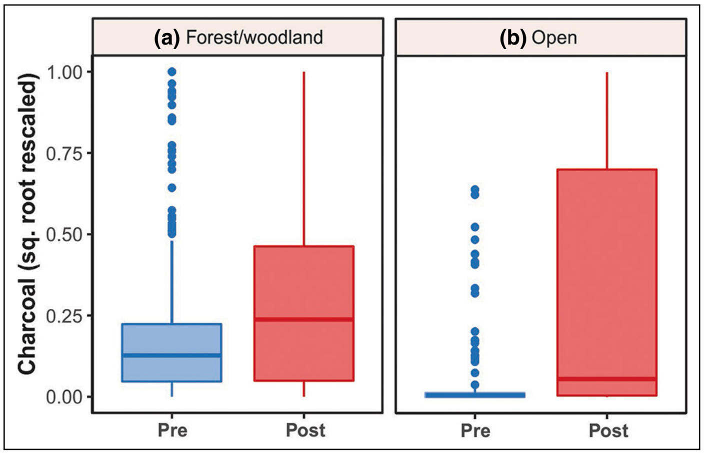

Figure 4. Regional patterns of pre- and post-colonial charcoal influx and variability, representing biomass burned. The fire history was reconstructed in (a) forest/woodland sites ($n = 48$) and (b) open vegetation sites ($n = 16$). Descriptions of horizontal lines, boxes, whiskers, and solid circles are the same as those in Figure 3. Additional information about the charcoal sites is presented in WebTable 1c.

forest vegetation, with different altitudes experiencing similar levels of biomass burning (WebFigure 5a). Following British colonization, a substantial increase in biomass burned across land-use areas is evident, especially within woodland/forest (Figure 4). The changing spatial distribution and variability of sedimentary charcoal accumulation (Figure 4; WebFigure 5) may represent the replacement of frequent, low-intensity, ubiquitous and patchy cultural burning with more localized, infrequent, high-intensity fire regimes since 1788 (Bradstock *et al*. 2002). This increase is particularly apparent at low elevations (WebFigure 5a), where colonial impacts were greatest due to large-scale land clearance for agricultural exploitation.

Post-colonial burning levels are higher and more variable than at any other time during the Holocene epoch (Bradstock *et al*. 2002; Mooney *et al*. 2011; Mariani and Fletcher 2017). The increase in charcoal post-1788 could be linked to (1) the cessation of Indigenous burning, promoting the accumulation of woody biomass conducive to more intense, large-scale fires; (2) post-colonial fire use targeting the removal of woody biomass for land clearance; and/or (3) recent changes in climate enhancing fuel dryness. These probable causes are not mutually exclusive, and effects are likely to be compounded. However, our combined land-cover change and biomass burning results indicate different trajectories in different land-use areas, which suggests that inconsistent management practices, rather than purely consistent climatic influences, may have played a key role.

Fire is affected by both top-down (eg regional climate) and bottom-up (eg local-scale topography, herbivory, human activity) factors (Rollins *et al*. 2002; Archibald *et al*. 2013; Whitehair *et al*. 2018). These bottom-up factors have been critical in parts of the Mediterranean Basin, where fire regimes have shifted dramatically due to the abandonment of rural burning practices (Pausas and Fernández-Muñoz 2012; Fréjaville and Curt 2015). If a top-down factor like climate change was solely responsible for the increase in biomass burned in southeast Australia post-1788, we would expect to see a coherent regional pattern, with all high-biomass areas experiencing increased burning (Pausas and Paula 2012). Instead, we detected greater burning in the forest/woodland zones (Figure 4), particularly at low-elevation sites (WebFigure 5a), corresponding to areas densely occupied by Indigenous groups at the time of British colonization. These areas were greatly affected by the 2019–2020 wildfire season (Boer *et al*. 2020). Fuel dryness and vegetation arrangement are the most important factors modulating the occurrence of wildfires in this region (Nolan *et al*. 2016). Long-term drought and extreme fire weather driven by climate change were responsible for fuel dryness during that season (Nolan *et al*. 2020). We suggest that the increased volume and connectivity of woody fuels, due to shrub thickening following the removal of Indigenous burning across entire landscapes, has contributed to unprecedented wildfire extent in these areas.

Restoring cultural landscapes for biodiversity and fire management

Cultural burning explicitly limits fire spread and maximizes biodiversity by creating pyrodiverse mosaics (Bliege Bird *et al*. 2016). Consequently, promoting fine-scale heterogeneity should also be the goal of fire management. Current management options to achieve this goal include hazard reduction burning, mechanical thinning, and reinstatement of cultural burning (Ximenes *et al*. 2017; Volkova and Weston 2019). Recent fires indicate that, as currently practiced, hazard reduction burning is insufficient to decrease fire risk, is often associated with poor biodiversity outcomes (Morrison *et al*. 1996), and disregards Indigenous peoples' cultural connection to the land (Whitehair *et al*. 2018; Fletcher *et al*. 2021). Mechanical thinning of canopy trees is regarded as ineffective and publicly unpalatable (Price and Bradstock 2012; Ximenes *et al*. 2017), but thinning of understory shrubs may be effective in reducing fuel connectivity to limit fire spread (Volkova and Weston 2019). We found that the current dense understory shrub layer is novel in the woodlands and forests of southeast Australian within the past 1000 years. Thinning this layer, through mechanical means or via cultural burning, could restore a vegetation structure more characteristic of pre-colonial times, when biomass burning was more stable. Of course, such interventions must be locally targeted to protect key cultural, biological, and economic assets, and their effectiveness should be carefully evaluated.

Although some scientists and resource managers advocate for cultural burning to minimize fire risk, cultural burning is much more than risk management, as it also provides demonstrable psychological, social, and cultural benefits (Burgess *et al*. 2009). It is a tangible demonstration of an ancient and profound connectedness between Indigenous peoples and place underpinned by reciprocity, sovereignty, ownership, and custodianship (Steffensen 2020). To manage the current fire crisis, we need to broaden our view of fire management to embrace traditional ecological knowledge and long-term ecology. Fire regimes cannot be divorced from humanity (Bowman *et al*. 2011). Indigenous cultural burning offers the potential to re-humanize many colonized landscapes, and in so doing safeguard against extreme wildfires and help decelerate the catastrophic biodiversity decline the continent has experienced since British colonization (Woinarski *et al*. 2015).

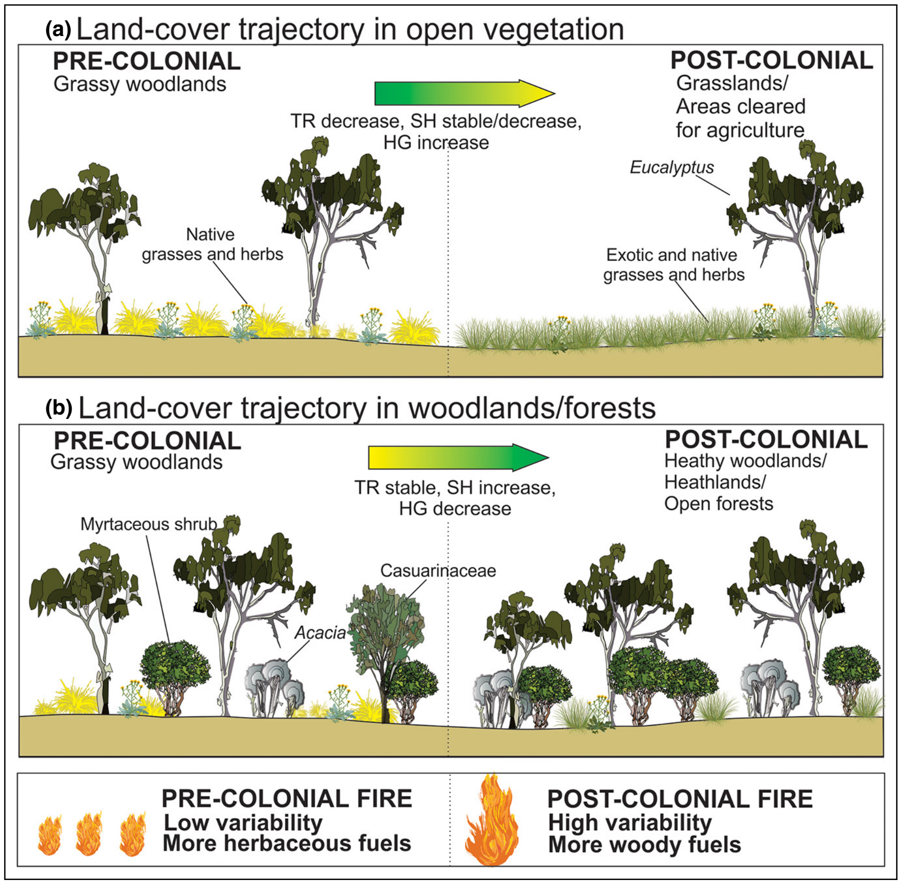

Figure 5. Schematic illustrating the transition from pre- to post-colonial landscape management according to our land-cover modeling results. The two panels represent the current regional vegetation settings analyzed in this study: (a) open vegetation and (b) forests and woodlands (current vegetation classification). The left side of the schematic represents the most abundant regional vegetation type pre-1788. Inferred changes in biomass burning based on current understanding of Indigenous burning practices are reported at the bottom of the figure. The two-letter abbreviations HG, SH, and TR are the same as those defined in Figure 1.

Conclusions

This paper provides new evidence for widespread changes in vegetation structure following the cessation of Indigenous cultural burning that established the foundation for the current fire crisis. Indigenous peoples of southeast Australia actively maintained grass-dominated ecosystems with 5–15% regional tree cover, corroborating historical documents and artworks depicting open woodlands and savanna-like landscapes. The cessation of cultural burning induced an increase in shrubby cover and a decline in grassy understories in today's forest/woodland areas, leading to changes in fuel availability and connectivity. We contend that Australia's current fire crisis can therefore trace its origins back to the colonial suppression of Indigenous cultural burning and subsequent attempts to suppress landscape fire. Our research informs debates about the role of disrupted Indigenous fire management in other landscapes; for example, there is growing acceptance that suppression of Indigenous fires in North America has contributed to uncontrollable wildfires associated with the accumulation of woody biomass in flammable forests. These findings enrich the global understanding of how Indigenous peoples maintained cultural landscapes over millennia, which were later misinterpreted by European colonists.

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Data Availability Statement

All data produced in this study are available in the main text, in the Supporting Information, or from the corresponding author upon request. Charcoal records are freely available through the Global Paleofire Database (www.paleofire.org; see WebTable 1b). Pollen records were partly presented in Herbert and Harrison (2016) and are being uploaded onto the Neotoma database (www.neotomadb.org) for free access.

References

Ali AA, Blarquez O, Girardin MP, *et al*. 2012. Control of the multimillennial wildfire size in boreal North America by spring climatic conditions. *P Natl Acad Sci USA* **109**: 20966–70.

Archibald S, Lehmann CE, Gómez-Dans JL, *et al*. 2013. Defining pyromes and global syndromes of fire regimes. *P Natl Acad Sci USA* **110**: 6442–47.

Birks HJB and Berglund BE. 2017. One hundred years of Quaternary pollen analysis 1916–2016. *Veg Hist Archaeobot* **27**: 271–309.

Bliege Bird R, Bird DW, and Codding BF. 2016. People, El Niño Southern Oscillation and fire in Australia: fire regimes and climate controls in hummock grasslands. *Philos T Roy Soc B* **371**: 20150343.

Boer MM, de Dios VR, and Bradstock RA. 2020. Unprecedented burn area of Australian mega forest fires. *Nat Clim Change* **10**: 171–72.

Borch M. 2001. Rethinking the origins of *terra nullius*. *Aust Historical Stud* **32**: 222–39.

Bowman D and Prior L. 2004. Impact of Aboriginal landscape burning on woody vegetation in *Eucalyptus tetrodonta* savanna in Arnhem Land, northern Australia. *J Biogeogr* **31**: 807–17.

Bowman DM, Balch J, Artaxo P, *et al*. 2011. The human dimension of fire regimes on Earth. *J Biogeogr* **38**: 2223–36.

Bowman DM, Williamson GJ, Abatzoglou JT, *et al*. 2017. Human exposure and sensitivity to globally extreme wildfire events. *Nature Ecol Evol* **1**: 0058.

Bowman DMJS, Balch JK, Artaxo P, *et al*. 2009. Fire in the Earth system. *Science* **324**: 481–84.

Bradstock RA. 2010. A biogeographic model of fire regimes in Australia: current and future implications. *Global Ecol Biogeogr* **19**: 145–58.

Bradstock RA, Williams JE, and Gill MA. 2002. Flammable Australia: the fire regimes and biodiversity of a continent. Cambridge, UK: Cambridge University Press.

Brookhouse M. 2006. Eucalypt dendrochronology: past, present and potential. *Aust J Bot* **54**: 435–49.

Burgess CP, Johnston FH, Berry HL, *et al*. 2009. Healthy country, healthy people: the relationship between Indigenous health status and "caring for country". *Med J Australia* **190**: 567–72.

Cary G, Dovers S, and Lindenmayer D. 2003. Australia burning: fire ecology, policy and management issues. Canberra, Australia: CSIRO Publishing.

Cary GJ and Banks JC. 2000. Fire regime sensitivity to global climate change: an Australian perspective. In: Innes JL, Beniston M, and Verstraete MM (Eds). Biomass burning and its inter-relationships with the climate system. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Clarkson C, Jacobs Z, Marwick B, *et al*. 2017. Human occupation of northern Australia by 65,000 years ago. *Nature* **547**: 306–10.

Colombaroli D, Mistry J, Milner A, *et al*. 2019. Diverse knowledge informing fire policy and biodiversity conservation. London, UK: Royal Holloway, University of London.

Enright NJ and Thomas I. 2008. Pre-European fire regimes in Australian ecosystems. *Geogr Compass* **2**: 979–1011.

Fletcher M-S, Hall T, and Alexandra AN. 2021. The loss of an indigenous constructed landscape following British invasion of Australia: an insight into the deep human imprint on the Australian landscape. *Ambio* **50**: 138–49.

Fréjaville T and Curt T. 2015. Spatiotemporal patterns of changes in fire regime and climate: defining the pyroclimates of south-eastern France (Mediterranean Basin). *Clim Change* **129**: 239–51.

Gaillard M-J, Sugita S, Mazier F, *et al*. 2010. Holocene land-cover reconstructions for studies on land cover–climate feedbacks. *Clim Past* **6**: 483–99.

Gammage B. 2011. The biggest estate on Earth. Melbourne, Australia: Allen and Unwin.

Gergis J, Neukom R, Gallant AJ, *et al*. 2016. Australasian temperature reconstructions spanning the last millennium. *J Climate* **29**: 5365–92.

Gott B. 2005. Aboriginal fire management in south-eastern Australia: aims and frequency. *J Biogeogr* **32**: 1203–08.

Griffiths T. 2001. Forests of ash: an environmental history. Cambridge, UK: Cambridge University Press.

Guiterman CH, Margolis EQ, Baisan CH, *et al*. 2019. Spatiotemporal variability of human–fire interactions on the Navajo Nation. *Ecosphere* **10**: e02932.

Hallam SJ. 2014. Fire and hearth: a study of Aboriginal usage and European usurpation in south-western Australia. Perth, Australia: UWA Publishing.

Harris S and Lucas C. 2019. Understanding the variability of Australian fire weather between 1973 and 2017. *PLoS ONE* **14**: e0222328.

Head L. 1989. Prehistoric Aboriginal impacts on Australian vegetation: an assessment of the evidence. *Aust Geogr* **20**: 37–46.

Herbert AV and Harrison SP. 2016. Evaluation of a modern-analogue methodology for reconstructing Australian palaeoclimate from pollen. *Rev Palaeobot Palyno* **226**: 65–77.

Hennessy K, Lucas C, Nicholls N, *et al*. 2005. Climate change impacts on fire-weather in south-east Australia. Canberra, Australia: CSIRO Publishing.

Hnatiuk R, Thackway R, and Walker J. 2009. Vegetation. In: The National Committee on Soil and Terrain (Eds). Australian soil and land survey field handbook (3rd edn). Melbourne, Australia: CSIRO Publishing.

Jones R. 1969. Fire-stick farming. *Australian Natural History* **16**: 224–28.

Kershaw P, Clark JS, Gill AM, *et al*. 2002. A history of fire in Australia. In: Bradstock RA, Elizabeth J, and Gill AM (Eds). Flammable Australia: the fire regimes and biodiversity of a continent. Cambridge, UK: Cambridge University Press.

Krawchuk MA, Moritz MA, Parisien M-A, *et al*. 2009. Global pyrogeography: the current and future distribution of wildfire. *PLoS ONE* **4**: e5102.

Larson ER, Kipfmueller KF, and Johnson LB. 2020. People, fire, and pine: linking human agency and landscape in the Boundary

Waters Canoe Area Wilderness and beyond. *Ann Am Assoc Geogr*; doi.org/10.1080/24694452.2020.1768042.

Mariani M and Fletcher M-S. 2017. Long-term climate dynamics in the extra-tropics of the South Pacific revealed from sedimentary charcoal analysis. *Quaternary Sci Rev* **173**: 181–92.

Mariani M, Connor S, Theuerkauf M, *et al*. 2016. Testing quantitative pollen dispersal models in animal-pollinated vegetation mosaics: an example from temperate Tasmania, Australia. *Quaternary Sci Rev* **154**: 214–25.

Mariani M, Connor SE, Fletcher MS, *et al*. 2017. How old is the Tasmanian cultural landscape? A test of landscape openness using quantitative land-cover reconstructions. *J Biogeogr* **44**: 2410–20.

Mooney S, Harrison S, Bartlein P, *et al*. 2011. Late Quaternary fire regimes of Australasia. *Quaternary Sci Rev* **30**: 28–46.

Morrison DA, Buckney RT, Bewick BJ, *et al*. 1996. Conservation conflicts over burning bush in south-eastern Australia. *Biol Conserv* **76**: 167–75.

Murphy BP, Bradstock RA, Boer MM, *et al*. 2013. Fire regimes of Australia: a pyrogeographic model system. *J Biogeogr* **40**: 1048–58.

Nolan RH, Boer MM, Collins L, *et al*. 2020. Causes and consequences of eastern Australia's 2019–20 season of mega-fires. *Glob Change Biol* **26**: 1039–41.

Nolan RH, de Dios VR, Boer MM, *et al*. 2016. Predicting dead fine fuel moisture at regional scales using vapour pressure deficit from MODIS and gridded weather data. *Remote Sens Environ* **174**: 100–08.

Pascoe B. 2014. Dark emu black seeds: agriculture or accident? Broome, Australia: Magabala Books.

Pausas JG and Fernández-Muñoz S. 2012. Fire regime changes in the western Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Clim Change* **110**: 215–26.

Pausas JG and Paula S. 2012. Fuel shapes the fire–climate relationship: evidence from Mediterranean ecosystems. *Global Ecol Biogeogr* **21**: 1074–82.

Price OF and Bradstock RA. 2012. The efficacy of fuel treatment in mitigating property loss during wildfires: insights from analysis of the severity of the catastrophic fires in 2009 in Victoria, Australia. *J Environ Manage* **113**: 146–57.

R Core Team. 2020. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Rollins MG, Morgan P, and Swetnam T. 2002. Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. *Landscape Ecol* **17**: 539–57.

Roos CI, Williamson GJ, and Bowman DM. 2019. Is anthropogenic pyrodiversity invisible in paleofire records? *Fire* **2**: 42.

Russell-Smith J, Whitehead P, Cooke P, and Yates C. 2009. Challenges and opportunities for fire management in fire-prone northern Australia. In: Russell-Smith J, Whitehead P, and Cooke P (Eds). Culture, ecology and economy of fire management in north Australian savannas: rekindling the *wurrk* tradition. Collingwood, Australia: CSIRO Publishing.

Steffensen V. 2020. Fire country: how Indigenous fire management could help save Australia. Melbourne, Australia: Hardie Grant.

Styger J, Marsden-Smedley J, and Kirkpatrick J. 2018. Changes in lightning fire incidence in the Tasmanian Wilderness World Heritage Area, 1980–2016. *Fire* **1**: 38.

Sugita S. 2007. Theory of quantitative reconstruction of vegetation I: pollen from large sites REVEALS regional vegetation composition. *Holocene* **17**: 229–41.

Theuerkauf M, Couwenberg J, Kuparinen A, *et al*. 2016. DISQOVER the Landcover-R based tools for quantitative vegetation reconstruction. Proceedings of the European Geosciences Union (EGU) General Assembly; 17–22 Apr 2016; Vienna, Austria. Munich, Germany: EGU.

Theuerkauf M, Kuparinen A, and Joosten H. 2013. Pollen productivity estimates strongly depend on assumed pollen dispersal. *Holocene* **23**: 14–24.

Vance T, Roberts J, Plummer C, *et al*. 2015. Interdecadal Pacific variability and eastern Australian megadroughts over the last millennium. *Geophys Res Lett* **42**: 129–37.

Vannière B, Blarquez O, Rius D, *et al*. 2016. 7000-year human legacy of elevation-dependent European fire regimes. *Quaternary Sci Rev* **132**: 206–12.

Volkova L and Weston CJ. 2019. Effect of thinning and burning fuel reduction treatments on forest carbon and bushfire fuel hazard in *Eucalyptus sieberi* forests of south-eastern Australia. *Sci Total Environ* **694**: 133708.

Whitehair L, Fulé PZ, Meador AS, *et al*. 2018. Fire regime on a cultural landscape: Navajo Nation. *Ecol Evol* **8**: 9848–58.

Whitlock C, Colombaroli D, Conedera M, and Tinner W. 2018. Land-use history as a guide for forest conservation and management. *Conserv Biol* **32**: 84–97.

Woinarski JC, Burbidge AA, and Harrison PL. 2015. Ongoing unraveling of a continental fauna: decline and extinction of Australian mammals since European settlement. *P Natl Acad Sci USA* **112**: 4531–40.

Ximenes F, Stephens M, Brown M, *et al*. 2017. Mechanical fuel load reduction in Australia: a potential tool for bushfire mitigation. *Aust Forestry* **80**: 88–98.

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