Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Shorter fire-return intervals rearrange fuel arrays in dry forests of southeastern Australia

Aaron E. Heap
a.e.heap@gmail.com
The University of Melbourne
Lauren T. Bennett
The University of Melbourne
Trent D. Penman
The University of Melbourne
Tom A. Fairman
The University of Melbourne

Research Article

Keywords: Flammability, Fire behaviour, Fuel structure, Alternative stable states, Fire vegetation feedback, State change, Eucalyptus

Posted Date: September 11th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10236356/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Shortening fire-return intervals are pushing fire-tolerant ecosystems in temperate Australia beyond their ecological limits, producing alternative vegetation states with markedly different composition and structure. While the structural effects of these regime shifts on fire-tolerant eucalypt forests are increasingly documented, their consequences for flammability remain largely untested. We compared fuel structure and load, surface fuel flammability, and modelled point-based fire behaviour between areas retaining a *Eucalyptus* overstorey under typical fire regimes (reference state) and alternative states in fire-tolerant native forests of southeastern Australia. Fuel hazard was visually assessed using an established field protocol, and surface fuels were sampled for laboratory flammability testing. Point-based fire behaviour was modelled using Vesta Mk2 across five weather scenarios spanning prescribed-burn to extreme wildfire conditions. Fuel hazard scores were significantly higher for surface and elevated strata in alternative states, but higher for near-surface and bark strata in reference states. However, laboratory flammability tests showed that surface fuels from alternative states were less ignitable, combustible, and consumable than those from reference states. Modelled fire behaviour showed consistently taller flames in alternative states across all weather scenarios, though rate of spread was greater only under the most extreme conditions. Spotting distances were consistently higher in reference states. These results show that alternative-state eucalypt forests produce a distinct fire behaviour signature: lower surface fuel flammability, greater flame height, but reduced spotting potential. The landscape-scale implications of this altered fire behaviour for subsequent fire regimes and the persistence of alternative states warrant further investigation.

Introduction

Fire shapes vegetation communities, but vegetation in turn shapes fire through its influence on fuel structure, flammability, and fire behaviour (Knox & Clarke, 2012; Loudermilk et al., 2022; Pausas & Bond, 2020). In fire-prone ecosystems, this relationship can lead to positive feedbacks, whereby changes in vegetation structure following disturbance alter fuel characteristics in ways that modify subsequent fire behaviour, favouring the persistence of altered states (Tepley et al., 2018; Tiribelli et al., 2018). As fire regimes intensify across the world (Bowman et al., 2020; Collins et al., 2021), the likelihood of disturbance-driven vegetation transitions that generate such feedbacks is increasing. However, greater empirical evidence is needed to understand how these transitions shape fuel and fire behaviour (Cawson et al., 2018; Gordon et al., 2024; Tiribelli et al., 2018). This is particularly true in southeastern Australia, where shortened fire-return intervals have driven transitions in *Eucalyptus*-dominated forests that may fundamentally alter point and landscape-scale fire dynamics.

Changing fire regimes have the potential to push plant species beyond their fire regime niche (Fairman et al., 2019; McColl-Gausden et al., 2021; Nolan et al., 2021). The fire regime describes patterns of fire frequency, severity, and seasonality (Krebs et al., 2010; Plumanns-Pouton et al., 2025). Because fire is a key mechanism facilitating recruitment in many Australian vegetation communities, plants have evolved a range of fire-adapted traits. These include facultative resprouting, obligate seeding, fire-triggered germination cues, and fire-stimulated flowering (Gill, 1975; Whelan, 1995). These traits typically support the regeneration of an ecosystem towards an assemblage that resembles the pre-fire species composition (Whitman et al., 2022). However, fire regimes are changing (Bowman et al., 2019; Kirchmeier-Young et al., 2019; Turco et al., 2019; Williams et al., 2019), and in many regions including southeastern Australia, fires are becoming more extensive, frequent, and intense (Collins et al., 2021; Nolan et al., 2020). When fire regimes no longer align with a species' fire adaptive niche, post-fire regeneration and vegetative recovery can fail leading to ecosystem reorganisation including transitions to an 'alternative state' (Coop et al., 2020; Falk et al., 2022; Steel et al., 2021).

Alternative ecosystem states are defined as persistent changes in community composition, structure, and function (Bielski et al., 2021; Coop et al., 2020; Knox & Clarke, 2012; Tiribelli et al., 2018). Vegetation assemblages and their spatial extent are typically governed by biophysical conditions, competition, and dominant growth forms (Pausas & Bond, 2020). However, in fire-prone ecosystems, regeneration and/or vegetative failure driven by altered fire regimes can lead to divergent vegetation trajectories developing under similar biophysical conditions (Guiterman et al., 2018; Pausas & Bond, 2020; Ramírez et al., 2025). Such transitions have been documented across a range of ecosystems, including shifts from forested to non-forested states (Dwomoh & Wimberly, 2017; Hirota et al., 2011; Paritsis et al., 2015). In some instances, transitions to alternative ecosystem states generate positive feedbacks, whereby changes in vegetation structure and composition increase flammability, reinforcing subsequent fire activity that favours the alternative ecosystem state (Luo et al., 2025; McLauchlan et al., 2020; Paritsis et al., 2015; Pausas & Bond, 2020; Tepley et al., 2018). In forests dominated by resprouting *Eucalyptus*, shortened fire-return intervals have been associated with resprouting failure and increased tree mortality (Fairman et al., 2019). This has resulted in transitions from tall open forest to alternative states characterised by low, closed canopies, dominated by small non-eucalypt tree and shrub species (Ashton & Chappill, 1989; Heap et al., 2026). Due to the limited dispersal ability of many eucalypt species, alternative states can persist for decades and often require management intervention to reintroduce the dominant tree species (Bassett et al., 2015; Booth, 2017; Bowd et al., 2023). In temperate forests of Australia, some have postulated that even-aged harvesting systems that maintain large areas of vegetation in juvenile states can lead to similar flammability feedbacks and increase fire severity (Bowd et al., 2023; Lindenmayer et al., 2011; Zylstra & Lindenmayer, 2025). However, understanding of these feedbacks remains largely conceptual, and the assumptions of the relationship between short-interval disturbances and fuel-fire feedbacks remain largely un-tested and un-quantified in the context of temperate Australia.

The reorganisation of forest structure following transitions to an alternative state, particularly the loss of the dominant tree canopy is likely to alter the fuel complex. Vegetation structure plays a central role in fire behaviour through its influence on fuel characteristics (Cruz et al., 2022; Zylstra et al., 2016). The composition and vertical arrangement of fuels govern ignition potential, flame development, and fire spread, with ecosystem structure directly linked to fire behaviour (Cruz et al., 2022; Zylstra et al., 2016). For this reason, fuel assessments globally consider these attributes when determining potential fire behaviour of an ecosystem (Mihajlovski et al., 2023; Ottmar et al., 2007; Taylor et al., 1997). Forest fuels are commonly

classified as fine and coarse fuels based on fuel components size. In the Australian context, fine fuel includes components < 6 mm thick including leaves, twigs, and bark (Hines et al., 2010). The vertical arrangement of the fuel complex is described in terms of fuel strata with each stratum having a distinct influence on fire behaviour and flammability (Cruz et al., 2022; Hollis et al., 2025). Forest surface fuels (or 'litter') typically including leaves, twigs, and bark and are often the source of ignition. Litter composition determines the aeration of surface fuels and therefore aspects of flammability (Burton, et al., 2023a). Near-surface fuels include seedlings, grasses, and prostrate shrubs that touch the ground. This stratum contributes to rate of spread by providing vertical connectivity between surface, elevated and bark fuels (Hines et al., 2010). Elevated fuels include upright vegetation in the understorey where the bulk of biomass occurs at the top of the structure, thereby influencing flame height. The combination of surface fuels and the near-surface and elevated fuels (understorey vegetation) can connect fire vertically to the canopy and are used to model flame height, fire-line rate of spread and intensity (Cruz, 2021; Cruz et al., 2022; Hollis et al., 2025). Bark fuels can provide a ladder for flames from the elevated fuels to the forest canopy. Moreover, they can form loose embers that become airborne and can establish spot fires influencing the forward spread of a fire (Gould et al., 2008; Hollis et al., 2025). Fuel components > 6 mm are referred to as coarse fuels and consist of fallen branches and logs. These take longer to dry and reach combustion, making them less available to burn. However, once ignited, these fuels are slow to be consumed and contribute significantly to residence time and heat outputs (Cawson et al., 2021; McArthur & Cheney, 2015). Together, these fuel attributes interact to determine the overall flammability of an ecosystem, encompassing its ignitability, combustibility, sustainability, and consumability (Zylstra, 2018).

Fire frequency is projected to increase in southeastern Australia and could lead to further forest state shifts or the expansion of alternative states in the landscape (Nolan et al., 2021). This highlights a critical need to understand how fuel structure, flammability, and fire behaviour differ between alternative and non-transformed (or 'reference') *Eucalyptus* forests. Despite growing recognition of the fuel differences in alternative states (Brown et al., 2021; Burton et al., 2019; Dwomoh & Wimberly, 2017; Tiribelli et al., 2018), few studies have quantified how structural differences between alternative and reference states translate to differences in fire behaviour. Given the strong link between forest composition, structure, and fire behaviour, it follows that alternative ecosystem states are likely to exhibit distinct fire behaviours (Paritsis et al., 2015). Wilsons Promontory National Park in temperate southeastern Australia provides a unique opportunity to measure the fuel structure of alternative states and understand the potential outcomes for flammability and fire behaviour. Throughout the park, patches of dry fire-tolerant eucalypt forest of varying size transitioned to alternative states following short-interval fires in the mid-twentieth century, resulting in the persistent loss of the *Eucalyptus* overstorey (Ashton & Chappill, 1989; Heap et al., 2025, 2026). These alternative states now coexist under similar biophysical conditions with adjacent forests where the *Eucalyptus* overstorey has persisted (reference forests), allowing direct comparison of fuel structure and fire behaviour between ecosystem states. In this study, we quantify differences in fuel structure, surface fuel flammability, and modelled fire behaviour between reference and alternative forest states. We combine field-based fuel assessments, laboratory flammability experiments, and point-based fire behaviour modelling across multiple fire weather scenarios to address four key questions:

(1) how do fuel structure and fuel loads differ between reference and alternative forest states?

(2) how does state change influence surface fuel flammability?

(3) how does state change influence point-based fire behaviour?

(4) do structural differences between alternative and reference states generate consistent differences in fire behaviour across weather conditions, indicating potential fuel-fire feedbacks?

By linking vegetation state to fuel characteristics and fire behaviour, this study provides mechanistic insight into whether and how fire behaviour differs between alternative and reference forest states, and evidence to understand if feedbacks might contribute to increased areas of alternative states under future fire regimes.

Methods

Study area

Wilsons Promontory National Park was chosen as our study landscape due to its fire history and identified examples of alternative forest states (Ashton & Chappill, 1989; Davies & Oates, 1999; Heap et al., 2025). The Park is 480 km^2 and located ~ 200 km from the city of Melbourne, Victoria, in southeastern Australia (Fig. 1). The park is the southernmost tip of Australia's mainland and has a temperate climate with mean monthly average temperatures ranging from minimum 12.2°C to a maximum 16.8°C and mean annual rainfall is approximately 1091 mm (1991–2020; Australian Government, Bureau of Meteorology, 2024). The narrow profile of the Park means it is heavily influenced by the marine climate and combined with highly variable topography and geology means it supports a diverse landscape of 32 mapped ecosystem types (DEECAa, 2025).

The Park includes ~ 23,047 ha of mixed-species temperate eucalypt forest. This study focuses on forests dominated by mixes of fire-tolerant resprouter eucalypts (*Eucalyptus obliqua, E. muelleriana*, and *E. baxteri)*, which occur at low elevation (9 to 659 m asl) and on drier northerly and westerly slopes. This vegetation type is locally classed as Shrubby Foothill Forest (SFF) (DEECAa, 2025). Characteristically, the ecosystem has an understorey of narrow-leaf shrubs and a ground storey of ferns, herbs, and graminoids. The typical fire regime for this ecosystem is fires through spring and summer with a return interval between 5–20 years with extreme fires occurring at 20–100 year intervals (Murphy et al., 2013). However, overlapping fires due to human ignitions and wildfires between 1939 and 1951 resulted in ~ 3000 ha of forests regenerating without a *Eucalyptus*

canopy, and converting to an alternative ecosystem state (Davies & Oates, 1999). About 352 ha of this alternative-state forest occurs across areas mapped as within the distribution of SFF (DEECAa, 2025) – see Heap et al. (2025) for a comprehensive summary of the fire history of Wilsons Promontory. Since 1951, two major bushfires have occurred at Wilsons Promontory. In 2005, an escaped fuel-reduction burn resulted in approximately 6,000 ha burnt across the lower portion of Wilsons Promontory including the location of the sites in this study. Then in 2009, ~ 24,000 ha was burned in the northern half of the park with very little crossover of the 2005 fire footprint (DEECAb).

Site selection

The study examined multiple sites within the mapped distribution of 'reference' and 'alternative' SFF. To ensure the alternative states once supported large *Eucalyptus* trees, polygons were overlaid on 1941 aerial imagery and examined for structures indicative of standing or fallen mature stems (Heap et al., 2025). Additionally, using satellite imagery from Google Maps (Google Maps, n.d.), the extent of alternative states was checked to account for any limited *Eucalyptus* encroachment at the margins of continuous forests into alternative states in the 27 years since mapping. These maps were used to select field sites in an alternative state. The current mapped extent of SFF was used in conjunction with satellite imagery to identify appropriate reference sites. In this study, reference sites were vegetation outside of the mapped areas of alternative states, where the fire history was consistent with the typical fire regime and where the *Eucalyptus* overstorey has persisted. Sites were selected to be a minimum of 50 m from roadsides, walking tracks, and forest ecotones. To prevent spatial confounding, sites were at least 150 m apart. All reference and alternative sites were within the 2005 wildfire footprint and limited to areas burned at either High or Extreme fire severity (i.e. High = Full canopy scorch and partial consumption; Extreme = Full canopy consumption: Gibson et al., 2020). In the field, sites were assessed to ensure consistency with the distribution of SFF (i.e. north or west-facing slope, at least 50 m from a gully line or waterway). Site-level observations included aspect, elevation, slope, eucalypt overstorey height, general species composition, and the type of bark fuel present (Table 1).

Table 1
Forest structural metrics summarised for Shrubby Foothill Forest occurring in alternative and reference states (mean ± standard error). Mean overstorey height in alternative states was calculated from 24 × 1 m² subplots distributed along two transects, whereas mean overstorey height in reference forests was estimated visually in the field.

Mean overstorey height (m)	**Reference State**	**Alternative State**
	19.0 ± 1.86	**4.7 ± 0.22**
Basal area (m^2)	51.3 ± 5.3	26.4 ± 2.9
Dominant *Eucalyptus* spp.	*Eucalyptus obliqua, E. muelleriana*	Absent to sparse *E. obliqua* and *E. baxteri*
Bark type of dominant spp.	Stringybark	Stringybark

Field-based fuel assessments

Assessment of fine fuels between February 2023 and March 2024 included litter sampling and the fuel hazard assessment method of Pickering et al. (2023), which extended the methodology of the Overall Fuel Hazard Guide (OFHG; Hines et al., 2010). The OFHG remains the primary operational tool used in southeastern Australia and provides coarse rapid assessment of fuel load. For this experiment we used the extended method of Pickering et al. (2023) to improve data quality and repeatability. In brief, the extended method averages measures of four fuel strata, using multiple points, along two intersecting transects (Figure S1; Supplementary Material). This method includes, measures of cover, height or depth, and the percentage of dead vegetation of: surface fuels, near surface fuels, elevated and bark fuels (Pickering et al., 2023; Fig. 2).

In the context of eucalypt forest, surface fuels are dead or decaying fine fuels laying on the ground and usually comprised of leaf litter, twigs, and bark fragments (< 6 mm; Gould et al., 2008). Near-surface fuels connect with the ground but are not laying on it (i.e. grasses). Elevated fuels have a distinct space between the ground and the fine fuels and are not continuously connected to the ground (i.e. shrubs and small trees: McColl-Gausden et al., 2025; Pickering et al., 2023; Table 1). Fuel structure was measured along two 33 m transects, intersecting at the plot centre and running north to south and east to west. Each fuel stratum was assessed within 1 m^2 quadrats at 20 points spaced evenly at 3 m intervals along the transect. Within each quadrat, surface fuel depth (mm) and cover (%) were measured. Total and dead cover were visually estimated to the nearest 5% for each of the surface, near-surface, and elevated fuel layers. The height of near-surface fuels and the top and base heights of elevated fuels were also measured. Bark fuels were assessed qualitatively within the 25 m radius by visually assessing the amount of charring and bark attached to the trunk by bark type (i.e. stringybark, ribbon bark, other bark) and bark fuel hazard scores were adjusted based on the basal area of the site (Pickering et al., 2023). To control for variability of observer bias in visual assessments, we used a single consistent assessor for all sites and final estimates were made in consultation with assisting team members. Mean measurements of each fuel stratum were summarised across the plot in conjunction with fuel hazard tables to estimate a fuel hazard score for each of the fuel strata (Pickering et al., 2023) – Low (1), Moderate (2), High (3), Very High (4), or Extreme (5).

Coarse fuels were measured along two 50 m transects also running NS and EW and intersecting at the plot centre. Coarse fuel was defined as fallen wood > 75 mm in diameter (Hollis et al., 2018) and was assessed for volume using a line-intercept method (Van Wagner, 1968). Each piece that

intersected one of the two transects was assessed for diameter at point of intersection, decay class (from 1 'sound' to 5 'rotten'), and remaining cross-sectional area (Aponte et al., 2014). Piece volume (m^3 ha^{-1}) was converted to biomass (t ha^{-1}) using wood density values by decay class from comparable eucalypt forests (Aponte et al., 2014) and summed per plot.

Lab based fuel assessments

Destructive samples of surface fuels collected from reference and alternative sites were assessed for flammability under laboratory conditions (Fig. 3c). Four samples of surface fuels were collected 10 m from the plot centre in each cardinal direction along the transects using a metal quadrat with an area of 0.09 m². Coarse woody debris, rocks and living plant material were excluded before drying the samples at 105°C to remove residual moisture and a constant weight was reached. The weight of the surface fuel samples for each sample was used to calculate t/ha, and bulk density (kg/cm^3). A sub-sample was retained, weighed, dried for an additional 48 hours and re-weighed to standardise for fuel moisture conditions.

The flammability of surface fuel samples was compared using an established laboratory methodology that has been proven to provide an accurate substitute for field-based flammability experiments (Burton, et al., 2023a). This method provides point-based measures of ignitability, combustibility, consumption and the fire sustainability of surface fuels (Grootemaat et al., 2015; Plucinski & Anderson, 2008; Zhao et al., 2021).

Surface fuels were reproduced in the laboratory by spreading individual dried litter samples across a tray at a depth consistent with field measures in metal trays that matched the dimensions of the collection quadrat, then sub-sampled using a 25-cm diameter ring to match the laboratory fire-containment ring (Fig. 3a reference fuels; **3b** alternative fuels). To represent ignition via a firebrand, a lit cotton cylinder (100% cotton, 3.5 cm length, 1 cm width, ~ 0.35 to 0.40 g) ignited using a gas butane lighter was dropped from ~ 30 cm above each fire-containment ring. This technique has been used to represent ignition via a eucalypt stringybark firebrand, a common firebrand and ignition source in Australian forests (Burton, et al., 2023a, 2023b; Cawson et al., 2022, 2024). Ignitability was measured as the probability of sustained ignition, combustibility as rate of flame spread, mass consumed as consumption, and flame duration as an indicator of sustainability. Ignition success was recorded when the flame had propagated fuels independently of the fire brand. Rate of spread was calculated as the time in seconds it took for the flame to reach the edge of the fire containment ring. Flame duration was measured as the time elapsed from ignition until flames and visible combustion ceased, and consumption was the mass of fuel consumed by burn as a percent of the total pre-burn mass. As per Burton et al. (2023a) flammability experiments were conducted within a flame propagation apparatus with the fume hood exhaust speed set at < 0.5 m/s (Fig. 3c**).**

Modelling Fire Behaviour

To evaluate potential fire behaviour in alternative and reference forest states, we used a combination of indicators calculated from the field-based assessments of fine and coarse fuels.

Fine fuels

Fire behaviour of the fine fuels were modelled using the Amicus application developed by CSIRO, which provides an interface for the Vesta Mk2 model for dry *Eucalyptus* forests (CSIRO, 2021). The Vesta Mk2 model predicts point-based fire behaviour metrics based on fine fuel loads and weather conditions, including rate of spread (m h^{-1}), flame height (m), fire-line intensity (kW m^{-1}), and spotting distance (m). The model has been validated in a range of eucalypt forest conditions (Cruz, 2021; Cruz et al., 2015), making it suitable for this study. Surface fuel load was calculated from the dried litter samples. As destructive sampling of live vegetation was not permitted in the National Park, fuel loads (t/ha) for the remaining fuel components (bark, elevated, and near-surface fuels) were estimated using field-assessed fuel hazard ratings in conjunction with the Indicative Fuel Loads table (Hines et al., 2010).

In Vesta Mk2, forward rate of spread is predicted from the combined load of surface and near-surface fuels, incorporating the average height of the understorey (calculated as the cover-weighted height of near-surface and elevated fuels; Cruz, 2021). Flame height, which influences fire-line intensity, is derived from both rate of spread and the height of elevated fuels (Cruz, 2021; Fairman et al., 2024). Fire behaviour was modelled across multiple weather scenarios to separate the relative influence of vegetation structure and weather on fire dynamics, and to assess whether differences between forest states were consistent across a range of fire-weather conditions. This approach also enabled evaluation of the extent to which vegetation-fire feedbacks were consistent or dependent on specific weather contexts. Furthermore, by incorporating scenarios representative of prescribed burning, typical wildfire conditions, and extreme fire events, the analysis provided outcomes directly relevant to fire management and decision-making.

Five weather scenarios were developed – four based on observed conditions associated with regional fire events, and one representing typical wildfire conditions ('*typical_cond*') in southeastern Victoria (Table 2). Observed scenarios were parameterised using the Keetch–Byram Drought Index (KBDI) and antecedent rainfall conditions corresponding to the days on which fires occurred. The *typical_cond* scenario was based on a fuel moisture content of 7% and a drought factor of 10 (Fairman et al., 2024). To represent milder fire weather conditions, prescribed burning scenarios were parameterised using weather conditions under which burns had previously been conducted. The *pb_low* scenario corresponded to a lower KBDI (19), while *pb_high* represented moderately drier conditions (KBDI = 37). As no fuel reduction burns have been conducted in dry *Eucalyptus* forests within Wilsons Promontory in the past two decades, prescribed burning conditions were derived from the nearest comparable forest type in Erica, Victoria (DEECA, 2021b). Wildfire scenarios (*wf_2005* and *wf_2009*) were based on weather conditions associated with major fire events within Wilsons Promontory in

2005 and 2009 (DECCA, 2021b; Su et al., 2024). Although weather conditions were considered suitable for planned burning, the 2005 burn developed into an extensive wildfire event. Conversely, the wildfire that occurred in 2009 occurred under extreme wildfire conditions associated with extensive catastrophic fires throughout the state (Dowdy et al., 2017).

The Vesta Mk2 *Eucalyptus* dry forest model was applied consistently across both vegetation states to minimise bias associated with using different fire behaviour models, despite alternative states being characterised by a low, closed understorey structure and a general absence of *Eucalyptus* overstorey. Remaining model inputs were standardised to minimise the influence of extraneous variation. For example, the wind adjustment factor of 3, open wind speed at 10 m height was fixed at 30 km h^{-1}, and slope was set to zero (Fairman et al., 2024). Rainfall inputs were derived from Australian Government, Bureau of Meteorology (2024) records and traced back to the most recent rainfall event prior to the fire of ≥ 1 mm and rainfall rounded to whole values to align with Amicus input constraints. KBDI was calculated using standard methods from the BARRA-C2 downscaled atmospheric dataset (Su et al., 2024).

Coarse fuels

For coarse fuels, we calculated two proxies from our measures of coarse fuel loads (Mg/ha): maximum total heat release (kJ/m²) and burnout (or residence) time (hours). Maximum total heat release estimates the potential maximum heat output of coarse fuel loads assuming full combustion and was calculated by multiplying heat yield (kJ/kg) by fuel quantity (kg/m²); heat yield in this study was assumed to be 15,000 kJ/kg as per McArthur and Cheney (2015). Burnout or residence time refers to the duration of flaming combustion and was calculated by dividing total heat release by combustion rate (assumed to be 11 kW/m², as per McArthur and Cheney, 2015), then converting the resulting value from seconds to hours.

Table 2

Descriptions of the five weather scenarios used in the Amicus fire behaviour modelling from the BARRA-C2 downscaled atmospheric dataset (Su et al., 2024). In the absence of recent planned burns of dry Eucalyptus *forests within Wilsons Promontory National Park, weather conditions for the closest recent planned burns of Shrubby Foothill Forests were used.*

Scenario	Keetch–Byram Drought Index	Last rainfall (> 1 mm)	Days since last rainfall	Fuel Moisture Content (%)	Drought Factor	Location	Year
pb_low	19	2.6	0	4.8	4.3	Erica	2015
pb_high	37	4.4	13	4.8	7.5	Erica	2008
typical_cond				7	10		
wf_2005	31	1.2	9	4.8	7.3	Wilsons Promontory	2005
wf_2009	96	1.2	28	4.8	10	Wilsons Promontory	2009

Data analysis

The following response variables were analysed: mean hazard score for each fuel stratum; cover (live and dead portions, %) and top height (m) of near-surface and elevated fuels; base height (m) of elevated fuels; cover (%), depth (mm), load (t/ha), bulk density (kg/m³), ignitability (*p*), sustainability (seconds), combustibility (mm/sec), and consumability (%) of surface fuels; and point-scale fire behaviour metrics — flame height (m), rate of spread (m/s), and spotting distance (m). Fire behaviour metrics derived from the Amicus application were evaluated across the five weather scenarios. Prior to analysis, data were assessed for compliance with model assumptions. Data that violated assumptions were transformed using either a logarithmic (+ 1) transformation or square root transformation, depending on data characteristics. Differences between states were tested using analysis of variance (ANOVA), with minimum significance set at $p < 0.05$ where assumptions were met. Where assumptions remained unmet following transformation, differences were tested using the Kruskal–Wallis test for single-factor comparisons, and the Aligned Rank Transform (ART) approach for factorial designs, which enables non-parametric analysis within an ANOVA framework (Wobbrock et al., 2011). For factorial analyses, models included scenario, state, and their interaction as fixed effects, and Type III tests were used to evaluate main and interaction effects. Where a significant scenario × state interaction was detected, differences between states within each scenario were tested using Tukey-adjusted estimated marginal means; where the interaction was non-significant, the main effect of state was interpreted directly. Differences among scenarios were assessed using compact letter displays derived from Sidak-adjusted comparisons of estimated marginal means. All statistical analyses were conducted in R (R Core Team, 2024).

Results

Field-Based Assessments

Fine Fuels

The elevated fuels in alternative states extended across a greater vertical profile than in reference states (2.83 m vs. 1.91 m, respectively). In alternative states, the mean base height was 1.9 m (± 0.16) and the top height 4.7 m (± 0.23), compared to 1.1 m (± 0.19) and 3.0 m (± 0.45) in

reference states ($p < 0.05$ for both). Cover in the elevated fuels was higher in alternative states, averaging 31% (± 4.62) compared with 15% (± 2.37; $p < 0.05$) in reference states. Dead cover was also higher in alternative states (ref = 17.5% ± 4.31 vs. alt = 14.1% ± 1.52), although the difference was not statistically significant. As a result, elevated fuel hazard scores were significantly higher in alternative states (3 ± 0.3) than in reference states (1.4 ± 0.22). Bark fuel hazard was significantly lower in alternative states, reflecting the near absence of *Eucalyptus* stems and lower basal area (ref = 2.9 ± 0.47 vs alt = 0.05 ± 0.52; $p < 0.001$). The high variability among alternative sites likely reflects the presence of spar-stage *Eucalyptus* individuals at two sites, which contributed small amounts of bark fuel to an otherwise bark-free fuel complex. Hazard scores of near-surface fuels were significantly lower at alternative than reference states (ref = 3.0 ± 0.00; alt = 2.5 ± 0.22; $p < 0.05$; Table 2). While near-surface fuel cover and height did not differ significantly between states, both were on average lower in alternative states. Surface fuel hazard scores were significantly higher in alternative states, averaging 3.9 (± 0.18; $p < 0.001$; Table 2) compared with 3.3 (± 0.15) in reference states. However, there was no appreciable difference in other surface fuel metrics between states. The surface fuels of alternative states were similar, averaging 28.8 mm (± 0.77) vs. 28.3 mm (± 1.83) in reference states, and cover was marginally higher 97.21% (± 0.95) vs. 97.85% (± 1.05). There was also negligible difference in surface fuel load between states, with alternative states 5% higher (20.06 ± 1.69 t/ha vs. 19.09 ± 1.19 reference), and in bulk density (alternative 70 kg/m^3 ± 10 vs. reference 90 ± 9).

Coarse Fuels

Although not statistically significant, the average weight of coarse fuels in alternative states was 52% lower than reference states (4.12 t/ha ± 1.2 alternative vs. 8.58 t/ha ± 2.43 reference). The mass of coarse fuels in alternative states was more consistent than reference states, which had two outlier sites with almost twice the mean.

Table 3
Mean (± SE) fuel structural attributes in reference and alternative states. Asterisks indicate significant differences between states (* $p < 0.05$, *** $p < 0.001$). Fine fuels (< 6 mm diameter) include surface, near-surface, elevated, and bark strata; coarse fuels (> 6 mm) are reported separately. Surface fuel depth and cover are means of 24 point-intercept samples per site, whereas load and bulk density were derived from four destructive samples. Differences between states were primarily evident in the elevated fuel stratum, with limited differences in surface and near-surface fuels and no significant differences in coarse fuel loads. Average fuel hazard scores were significantly higher in alternative states across all fine fuel strata.

Fuel Layer	Fuel Measure	Reference State	Alternative State	
Surface Fuels	Cover (%)	97.2 (± 0.95)	97.9 (± 1.05)	
	Depth (mm)	28.9 (± 1.76)	28.3 (± 1.84)	
	Load (t/ha)	19.1 (± 1.20)	20.1 (± 1.69)	
	Bulk Density (kg/m^3)	90 (± 9)	70 (± 10)	
	Mean Hazard Score	3.3 ± 0.15	3.9 ± 0.18	*
	Description	Aerated litter with variation in leaf and small stem parts. Extensive leaf curl	Densely packed litter of very fine leaves ~ 4–6 mm in width	
Near-surface Fuels	Cover (%)	26.2 (± 1.62)	21.1 (± 2.7)	
	Top Height (m)	0.5 (± 0.04)	0.4 (± 0.04)	
	Dead Cover (%)	55.7 (± 5.14)	61.3 (± 3.88)	
	Mean Hazard Score	3.0 (± 0)	2.5 (± 0.22)	*
	Description	Dense, near consistent layer of fuels, generally live. Easy to walk through *Epacris impressa*, Goodenia ovata, and Pteridium esculentum	Lower cover of near surface fuels than reference forests but a greater proportion of dead fuel. Generally, *Goodenia ovata* and *Pteridium esculentum*	
Elevated Fuels	Cover (%)	14.5 (± 2.37)	31.3 (± 4.62)	*
	Top Height (m)	3.0 (± 0.45)	4.7 (± 0.23)	*
	Base Height (m)	1.1 (± 0.19)	1.9 (± 0.16)	*
	Dead Cover (%)	14.1 (± 1.52)	17.5 (± 4.31)	
	Mean Hazard Score	1.4 (± 0.22)	3 (± 0.3)	***
	Description	Patchy cover of *Acacia verticillata* and *Pomaderris aspera. Very easy to walk through*	Densely packed canopy dominated by small leaf species such as *Acacia verticillata* and *Kunzea ambigua*	
Bark Fuel	Description	Dominated by many large stringy bark species such as *E. obliqua, E. muelleriana*	Generally, bark types that are quite firmly held. The exception of small *Kunzea ambigua* stems that were loose and papery. Spar stage E. obliqua, E. baxteri present in 2 plots	
	Mean Hazard Score	2.9 (± 0.47)	0.05 (± 0.52)	***
Coarse Fuels	Weight (t/ha)	8.6 (± 2.43)	4.2 (± 1.2)	

Laboratory-Based Assessments – Surface Fuel Flammability

Laboratory-assessed flammability of surface fuels differed significantly between forest states across multiple metrics. Lab-based flame propagation experiments indicated that surface fuels in alternative states were less ignitable, less combustible, and less consumable relative to reference areas. The probability of sustained ignition was 0.58 in samples from alternative states and 0.95 in samples from reference states (Fig. 4a; $p < 0.001$). Surface fuel from alternative states took 67% longer to ignite relative to reference states (37.8 ± 5.19 seconds vs. 22.5 ± 3.70; $p < 0.05$). This was despite samples from alternative states having lower fuel moisture content (1.37 ± 0.09% vs. 1.87 ± 0.14; $p < 0.001$). Sustainability of fire between states was comparable (Fig. 4b; 280.9 sec ± 35.04 alternative vs 283.28 ± 15.22 reference). In contrast, consumability and combustibility were substantially reduced in alternative states. Mean fuel consumption was 296.4 gm/m^2 (± 67.0) in alternative state samples compared with 969.8 gm/m^2 (± 87.5) in

reference samples (Kruskal-Wallis rank sum test, $p < 0.001$; Fig. 4d), and only 37% of successful ignitions in alternative samples reached the edge of the ring before extinguishing, compared with 92% in reference samples ($p < 0.001$). Consistent with this, combustibility was lower in alternative samples (0.99 ± 0.09 mm/s) than in reference samples (1.85 ± 0.17 mm/s; $p < 0.001$; Fig. 4c). Maximum flame height was also markedly lower in alternative (5.0 ± 1.70 cm) than reference states (24.7 ± 1.93 cm; $p < 0.001$ data not shown).

Modelled - Fire Behaviour

Fine fuels

Modelled fire behaviour differed between states, though whether the difference varied among fire-weather scenarios depended on the metric. Mean flame heights were significantly higher in alternative than reference states, and this difference was consistent across all weather scenarios (main effect of state $p < 0.001$; state × scenario interaction non-significant; Fig. 5a). Flame heights in alternative states ranged from 6.4 m to 32.8 m, compared with 2.2 m to 25.5 m in reference states. In contrast, predicted rates of spread were comparable between states under the prescribed burning and moderate wildfire scenarios, differing significantly only under the most extreme conditions (wf_2009; $p < 0.01$).

Spotting distances were consistently different between forest states across the modelled fire scenarios. In reference states, spotting distances increased with fire weather severity, ranging from 1246 m (± 495) under *pb_low* conditions to 5253 m (± 62.8) under *wf_2009*. Spotting distances were also high under *pb_high* (4605 ± 184 m) and *wf_2005* (4417 ± 220 m) scenarios. Conversely, mean spotting distances in alternative states were comparatively low across scenarios, ranging from 383 ± 262 m under *pb_low* to 1078 ± 719 m under *wf_2009*. Spotting distances differed significantly between states under all scenarios except *typical_cond* with reference forests consistently producing greater spotting distances (pb_low: $p < 0.001$; pb_high: $p < 0.01$; wf_2005: $p < 0.05$; wf_2009: $p < 0.001$).

Coarse Fuels

There was no significant difference in the simulated fire behaviour based on coarse fuels between the two states. On average the estimated heat release from a fire in an alternative state was 6180 MJ/m^2 (± 1799) compared to 12876 MJ/m^2 (3649) in reference states (data not shown). Furthermore, average burnout time for coarse fuels in alternative states was 0.16 (± 0.05) hours compared to 0.33 (± 0.09) hours.

Discussion

Differences in the flammability of alternative and reference states depended on how flammability was measured. Field-based fuel hazard, laboratory surface fuel flammability, and modelled fire behaviour did not consistently identify the same state as the more flammable. This is likely due to each capturing a different component of the fuel complex and a different phase of fire. Lower surface fuel flammability indicated that alternative states are less susceptible to ignition via spotting. Once burning, however, their taller and denser elevated fuels support greater flame heights and faster spread under the most severe weather. Alternative states are therefore harder to ignite but capable of more intense fire behaviour once alight. Considered together rather than in isolation, these measures suggest a pathway from surface ignition toward canopy involvement, in which reduced ignitability and intensified vertical fire behaviour are properties of the same altered fuel structure.

Structural reorganisation following canopy loss increases fuel hazard despite limited change in individual metrics

In the Australian context, the relative importance of different fuel components in driving fire behaviour remains under debate (Nolan et al., 2024). For instance, surface fine fuel load was historically considered a significant predictor of rates of fire spread (McArthur, 1967; Noble et al., 1980) and this relationship remains robust for low-intensity surface fires (Cruz, 2021). However, understorey height becomes more influential than understorey fuel load in producing moderate to high intensity fires that move vertically through the fuel complex (Cruz et al., 2022). For fires to transition from surface to canopy fuels, ladder fuels, such as elevated shrubs and bark are required to vertically connect the fuel profile (Cruz et al., 2022; McArthur, 1967; Van Wagner, 1977). Bark fuels also contribute to firebrand production, facilitating spotting and forward fire spread (Cruz et al., 2022; Nolan et al., 2024; Penman et al., 2017). Therefore, with no difference in surface fuel load between states, a main difference in fire behaviour between alternative and reference states could be greater flame heights associated with the taller and denser mid-storey (elevated) fuels in alternative states. However, the absence of a tall canopy and bark fuels in alternative states implies a lower likelihood of rapid spread due to a lower potential for canopy propagation and bark-related spotting (Ellis, 2011; Ganteaume et al., 2009).

Although coarse fuel loads were lower in alternative states, this difference was not statistically significant. Mean coarse fuel mass in the case study reference forests (9 Mg ha^{-1}) was substantially lower than values reported for long-unburnt or less-disturbed *Eucalyptus* forests that, for example, range from 16 Mg ha^{-1} (Fairman et al., 2024) to 45 Mg ha^{-1} (Aponte et al., 2014). Large trees are the primary source of coarse woody debris mass, and their absence in alternative states explains the lower coarse fuel loads in alternative states (Harmon et al., 1986; Woldendorp & Keenan, 2005). The relatively low CWD mass in this study is likely explained by the relatively short time since the last wildfire (20 years) relative to the other comparable forests. With increasing time since fire, coarse fuels would be expected to accumulate in reference forests due to senescence-related tree fall. Over longer timeframes, this difference in coarse fuel mass is likely to widen, as reference forests continue to accumulate coarse woody debris from large trees while alternative states which lack them do not. This could mean future changes in measures linked to coarse fuel loads such as heat release,

smouldering time, smoke release, and ease of suppression between states (Albini & Reinhardt, 1995; Fairman et al., 2024; Hyde et al., 2011). Although visual fuel hazard assessments have recognised limitations, including observer bias and inconsistencies with measured fuel loads (Cruz, 2024; Hollis et al., 2025) several steps were taken to minimise these in this study. All assessments were conducted by a single observer and repeated along transects. Furthermore, by presenting both the composite hazard index per stratum and its individual components, we enable a transparent evaluation of how different fuel attributes contribute to overall fire hazard.

Species turnover alters surface fuel traits and reduces flammability in alternative states

Shifts in the dominant plant species within alternative states altered surface fuel traits in ways that changed surface fuel flammability. Despite no significant differences in surface fuel load between states, and the higher hazard score of alternative states, laboratory flammability experiments demonstrated that surface fuels in alternative states were less ignitable and less combustible. Although the sustainability of the fire was comparable between states, less of the fuel of alternative states was consumed. Leaf and litter traits are known to strongly affect fuel flammability by influencing packing density, aeration, moisture retention, and heat transfer (Burton et al., 2020; Scarff & Westoby, 2006). The dominance of small-leaved shrubs and small-tree species such as *Kunzea ambigua* and *Acacia verticillata* in alternative states (Ashton & Chappill, 1989; Costermans, 2009; Heap et al., 2026; Plucinski & Anderson, 2008) is therefore likely to produce more compact litter beds with reduced aeration, limiting oxygen availability, heat transfer and constraining flame spread (Engber & Varner, 2012; Grootemaat et al., 2015; Schwilk & Caprio, 2011). In contrast, the larger leaves of *Eucalyptus* species typically have more surface area and leaf curl, forming more aerated litter beds that promote flammability (Burton, et al., 2023b). Similar reductions in litter flammability have been reported in systems where overstorey composition shifts away from flammable tree species following fire exclusion and vegetation transition (Kreye et al., 2018). Although higher basal area in reference states would be expected to generate greater surface fuel loads due to strong links between basal area and litter production (Fox et al., 1979; Heap et al., 2026; Turnbull & Madden, 1983), no such difference was detected at our field sites. Greater inputs from the denser shrub and small-tree layers of alternative states may offset their lack of overstorey *Eucalyptus* litterfall, producing comparable surface fuel loads across states.

Flame height and rate of spread diverge between states

Differences in modelled fire behaviour between states reflected the distinct fuel hazard and elevated fuel attributes of each state, and how those attributes are weighted within the Vesta Mk2 model. For example, simulated flame height was consistently higher in alternative states regardless of the weather scenario. This would be explained by the contribution of understorey (elevated fuel) height to the flame height calculation, regardless of the phase of fire initiation, and is consistent with the known sensitivity of the model to the height of elevated fuels (Cheney et al., 2012; Cruz, 2021; Zylstra et al., 2016). Understorey fuel heights (calculated as the cover-weighted height of near-surface and elevated fuels) recorded in alternative states exceeded the standardised fuel conditions used to parameterise the Vesta Mk2 model up to (2.8 m; Cruz, 2021). This introduces uncertainty into the absolute magnitude of predicted fire behaviour differences. However, the consistently greater flame heights in alternative states across all scenarios, is mechanistically consistent with the known sensitivity. In contrast, rate of spread differences between states were conditional on the severity of fire weather and were only significant under the *wf_2009* scenario, which burned under catastrophic weather conditions. This result also likely reflects the structure of the Vesta Mk2 model where understorey fuel height only influences rate of spread when the fire moves from the surface and near-surface combustion phase to elevated and bark fuels under lower fuel moisture contents. Therefore, under the prescribed burning and moderate weather scenarios the modelled fire behaviour likely remained in a phase where surface and near-surface fuel loads were the primary drivers of rate of spread and did not differ significantly between states.

The mechanism underlying the significantly higher rate of spread predicted in alternative states under *wf_2009* conditions is not entirely clear from the modelling alone. We propose two likely explanations, given the stepwise nature of modelled fire escalation through successive fuel strata in dry eucalypt forests. The taller understorey of alternative states might increase the likelihood of fire propagating through the full fuel complex under extreme fire weather, generating a higher weighted rate of spread in the integrated model output. Alternatively, the elevated fuel height difference between states may be sufficient to sustain higher rates of spread in the elevated and bark fuels before both states initiate ignition of the full fuel complex. That is, rate of spread is driven predominantly by wind speed and fuel moisture rather than fuel structure in the model (Cruz, 2021). To distinguish what is the most likely explanation would require wildfire observations, which was outside the scope of this study. However, under the most extreme fire weather conditions, the influence of localised fuel type and structure on fire behaviour diminishes considerably as weather becomes the dominant driver of fire spread across a landscape (Collins et al., 2023; Fernández-Guisuraga & Calvo, 2025; Wang et al., 2022).

Spotting distances reflect bark fuel presence rather than fire weather

The increase in simulated spotting distances from *pb_low* to other scenarios in our study could be attributed to the development of convective activity rather than wind speed (Thurston et al., 2016), as wind speed was held constant across all fire weather scenarios. With greater KBDI, rising fire intensity would have driven stronger convective plume development in the model, lofting firebrands to greater heights and distances (Koo et al., 2010). The dominant bark type in the reference states was stringybark *Eucalyptus spp.*, which are associated primarily with short to medium-range spotting through the production of fibrous bark fragments (Cruz, 2021; Hodgson, 1967; McArthur, 1967). Ribbon or decorticating bark species that produce aerodynamically efficient firebrands capable of long combustion times and extended transport distances were generally absent. This likely explains why maximum spotting distances in reference states peaked at 5253 m under the most extreme fire weather scenario, which is at the lower end of the long-range spotting threshold (Cruz, 2021).

As expected, the near-absence of bark fuels in alternative states resulted in negligible firebrand production and insensitivity of spotting distances to the fire weather scenarios. The exception to this pattern was the *typical_cond* scenario, under which spotting distances did not differ significantly between states. This likely reflects the higher fuel moisture content applied in this scenario (7% compared to 4.8% in all observed fire weather scenarios), which would reduce the predicted fire intensity and spotting potential in both states. Unlike the observed fire weather scenarios parameterised using KBDI values and antecedent rainfall records, *typical_cond* applied a fixed drought factor of 10 overriding the need for a KBDI input, representing an idealised rather than empirically grounded set of conditions (Fairman et al., 2024). The combination of higher fuel moisture content and the absence of an empirically derived antecedent dryness index may have reduced the sensitivity of the model to fuel structural differences between states under this scenario.

The Vesta Mk2 model has been evaluated against independent datasets of experimental fires and well-documented wildfires across southern Australia, demonstrating mean absolute errors consistent with or lower than other empirically based fire spread models. We acknowledge the potential limitations of using the Vesta Mk2 model to predict fire behaviour in the alternative states that more closely resemble a tall shrubland in structure, which could lead to conservative fire behaviour estimates. Nonetheless, application of a single model – Vesta Mk2 – in our study minimised the potential for confounding errors in using different models for our between-state comparisons.

Implications for management

A key outcome of this study is that the flammability of alternative states cannot be adequately characterised by any single assessment method. In isolation, different methods provide contrasting results depending on the part of the fuel complex examined. However, when examined collectively, these different measures of flammability start to illustrate the potential pathway from spotting to canopy ignition in landscapes where alternative states exist. For instance, the potential risk of surface fuel ignition and spread via spotting is lower in alternative states. Despite similar individual fuel measurements, lower surface fuel flammability, combined with lower aggregated near-surface fuel hazard scores in alternative states could limit the risk of fire transferring from the surface into the elevated fuel layer (Zylstra et al., 2016). However, this risk may intensify once a surface fire transitions into elevated fuels, or if a fire front encountered patches of alternative vegetation. Modelled flame heights predicted in alternative states (mean 18 m across scenarios) would be sufficient to ignite surrounding *Eucalyptus* canopies (~ 19 m), potentially exacerbating vertical and horizontal fire spread into surrounding forests. Furthermore, large coarse fuel structures such as logs can retain moisture and interrupt fuel continuity, potentially forming localised barriers to fire spread. Their scarcity in alternative states may therefore remove a source of discontinuity in the fuel bed. This may allow more continuous heat transfer pathways by limiting interception of radiant heat and maintaining flame fuel contact; thereby, increasing the efficiency of energy transfer required for sustained fire spread (Andrew et al., 2000; Sullivan et al., 2018). Management should explicitly distinguish between ignition risk and suppression difficulty when assessing fire hazard. Although alternative states may be characterised by lower surface fuel hazards, their altered vertical structure can support more intense and fast-spreading fires once ignited.

This study focused on point-based assessments of fuel hazard and modelled fire behaviour, which limits inference at landscape scales. In this landscape alternative states occur across a range of vegetation types, topography, and environmental gradients (Davies & Oates, 1999). Therefore, future research should explicitly examine how spatial arrangement, extent, and connectivity of alternative states interact to influence landscape-scale fire behaviour. Furthermore, alternative states resemble vegetation types typically associated with low productivity and higher aridity, yet in this study they occurred in environments capable of supporting tall forests, potentially with wetter soils. This mismatch between vegetation structure and site productivity potential may have important implications for fuel moisture dynamics (Brown et al., 2021), that warrant further investigation. For example, at the base of the profile, the dense layer of small, compacted surface fuels may trap and retain moisture at the litter/soil interface, further dampening ignition potential. Predicted fuel loads across landscapes are often based on biophysical conditions (Marshall et al., 2024; McColl-Gausden et al., 2020; Pickering et al., 2025) but rarely account for the divergent fuel conditions associated with state changes. This presents a further opportunity to develop dynamic fuel models that account for the potential change in fuels structure associated with changed forest states induced by short-interval fires.

By generating fire-behaviour differences that persisted across weather conditions, the altered fuel structure of alternative states provides a mechanism for fuel-fire feedbacks that could reinforce their persistence under future fire regimes.The development of fuel complexes that modify fire behaviour are expected to promote the persistence of these alternative states (Ramírez et al., 2025; Schwörer et al., 2024; Tepley et al., 2018; Tiribelli et al., 2018). Transitions to non-forest vegetation by shortened fire return intervals have been documented in other fire-prone ecosystems, where positive fire-vegetation feedbacks maintain early successional, shrub-dominated states (Tepley et al., 2018; Thomsen et al., 2025; Wei et al., 2024). Such fuel-mediated feedbacks provide a clear mechanistic pathway through which alternative states can be stabilised under similar biophysical conditions (Beisner et al., 2003; Cheng et al., 2025; Scheffer et al., 2001). By shaping subsequent fire behaviour, the presence of alternative states, in conjunction with projected changes to fire regimes, may facilitate their expansion across the landscape (Lindenmayer et al., 2011; McDowell et al., 2020). In the context of our case-study landscape, these results suggest that feedbacks maintaining the alternative state may operate through intensified fire behaviour once fire is established, rather than through increased ignitability. In particular, the greater flame heights, and faster spread under extreme weather, could promote canopy ignition and conversion of adjacent forest. This dynamic is further compounded by the limited capacity of *Eucalyptus* species to recolonise patches that have transitioned to an alternative state (Booth, 2017; Bowd et al., 2023). Therefore, returning these alternative states to a fuel structure comparable to the reference condition would require substantial intervention, including the reintroduction of *Eucalyptus* following fire and the exclusion of subsequent fire until trees reach an adequate escape size (Cheal, 2010; Fairman et al., 2019).

Conclusion

This study compared fuel structure, surface fuel flammability, and modelled fire behaviour between reference and alternative forest states in Wilsons Promontory National Park, southeastern Australia, to understand how short-interval fires alter the fuel complex and the implications for subsequent fire behaviour. The results indicate that transitions to an alternative state produce a distinct fuel profile and differences in fuel hazard scores but might not be adequately characterised by any single assessment method.

Fuel structure between states differed primarily in the aggregated Overall Fuel Hazard scores. Surface and elevated fuel hazard scores were significantly higher in alternative states, while near-surface and bark scores were higher in reference states. This was despite significant differences in individual fuel metrics being limited to cover and the top and base heights of the elevated fuel layer. Bark fuels were effectively absent in alternative states following the loss of the *Eucalyptus* overstorey, representing the most tangible difference in fuel hazard between states. Laboratory-based surface fuel flammability was lower in alternative states across multiple metrics, including ignitability, combustibility, and consumability. This reflected differences in leaf morphology that influence litter packing, which are not captured by surface fuel load alone. Modelled fire behaviour revealed consistently higher flame heights in alternative states across all fire weather scenarios, driven by taller and denser elevated fuel structure, while rate of spread differed only under the most extreme fire weather conditions. Spotting distances also diverged between states across most scenarios: reference forests showed strong weather-dependent escalation, driven by firebrand production from stringybark fuels, whereas alternative states remained low and weather-insensitive owing to the near-absence of bark fuels. These results reinforce the potential for state-dependent feedbacks, as the limited spotting capacity of alternative states reduces their likelihood of seeding fire into adjacent forest. Together, these findings indicate that alternative states would be harder to ignite via spotting and less combustible at the surface, yet capable of more intense fire behaviour once burning, such as higher flame heights. This points to fuel-mediated fire behaviours consistent with the persistence of alternative states under future fire regimes: reduced ignition probability and spotting potential may limit the frequency of fire entering alternative-state patches, while the intense fire behaviour generated once ignition occurs has the potential for flame-driven canopy ignition in adjacent reference forest and may accelerate the conversion of surrounding vegetation to alternative states over time.

These findings have implications for fire management in landscapes where alternative states are present or have the potential to expand under a drier climate. Relying on surface fuel metrics alone to assess fire hazard in alternative states risks underestimating flame height potential while overestimating ignition risk. Future research should examine how the spatial arrangement, extent, and connectivity of alternative states interact to drive landscape-scale fire behaviour.

Declarations

Author Contribution

AH: Conceptualisation, investigation, funding acquisition, writing – original draft, methodology, validation, visualisation, writing – review and editing, formal analysis, project administration, resources, data curation. LB: review and editing, methodology, supervision. TF: conceptualisation, funding acquisition, methodology, review and editing, supervision. TP: conceptualisation, editing, methodology, resources, supervision.

Acknowledgement

I pay my respects to the Traditional Owners of the land that non-Indigenous Australians call Wilsons Promontory National Park: the Boonwurrung, Bunurong and Gunaikurnai peoples. This research was made possible by an Australian Government Research Training Program Scholarship, funded by the Commonwealth and awarded to Aaron Heap (PhD candidate) [DOI: https://doi.org/10.82133/C42F-K220], with further support from the Parks Victoria Research Partnerships Program and The Friends of Wilsons Promontory. I am grateful to Brooke Love and Jim Whelan, both formerly of Parks Victoria, for so generously sharing their deep field knowledge and historical insight into Wilsons Promontory. Fieldwork was additionally supported by the Victorian Environmental Assessment Council's Bill Borthwick Student Scholarship and the Samuel Austin Frank Pond Travelling Scholarship. Finally, I thank all the volunteers who gave their time and energy to help with fieldwork.

Data Availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request. This study did not involve any clinical trials therefore, Clinical trial number: Not applicable.

References

1. Albini, F., & Reinhardt, E. (1995). Modeling Ignition and Burning Rate of Large Woody Natural Fuels. *International Journal of Wildland Fire*, *5*(2), 81–91. https://doi.org/10.1071/WF9950081
2. Andrew, N., Rodgerson, L., & York, A. (2000). Frequent fuel-reduction burning: The role of logs and associated leaf litter in the conservation of ant biodiversity. *Austral Ecology*, *25*(1), 99–107. https://doi.org/10.1046/j.1442-9993.2000.01015.x
3. Aponte, C., Tolhurst, K. G., & Bennett, L. T. (2014). Repeated prescribed fires decrease stocks and change attributes of coarse woody debris in a temperate eucalypt forest. *Ecological Applications*, *24*(5), 976–989. https://doi.org/10.1890/13-1426.1

4. Ashton, D. H., & Chappill, J. A. (1989). Secondary succession in post-fire scrub dominated by Acacia verticillata (L'Herit.) Willd. At Wilsons Promontory, Victoria. *Australian Journal of Botany*, *37*, 1–18. https://doi.org/10.1071/BT9890001
5. Australian Government, Bureau of Meteorology. (2024, May 21). *Climate statistics for Australian locations*. Bureau of Meteorology. http://www.bom.gov.au/jsp/ncc/cdio/cvg/av?p_stn_num=085096&p_prim_element_index=0&p_comp_element_index=0&redraw=null&p_display_type=statistics_summary&normals_years=1991-2020&tablesizebutt=normal
6. Bassett, O. D., Prior, L. D., Slijkerman, C. M., Jamieson, D., & Bowman, D. M. J. S. (2015). Aerial sowing stopped the loss of alpine ash (Eucalyptus delegatensis) forests burnt by three short-interval fires in the Alpine National Park, Victoria, Australia. *Forest Ecology and Management*, *342*, 39–48. https://doi.org/10.1016/j.foreco.2015.01.008
7. Beisner, B. E., Haydon, D. T., & Cuddington, K. (2003). Alternative stable states in ecology. *Frontiers in Ecology and the Environment*, *1*(7), 376–382.
8. Bielski, C. H., Scholtz, R., Donovan, V. M., Allen, C. R., & Twidwell, D. (2021). Overcoming an "irreversible" threshold: A 15-year fire experiment. *Journal of Environmental Management*, *291*, 112550. https://doi.org/10.1016/j.jenvman.2021.112550
9. Booth, T. H. (2017). Going nowhere fast: A review of seed dispersal in eucalypts. *Australian Journal of Botany*, *65*(5), 401. https://doi.org/10.1071/BT17019
10. Bowd, E. J., McBurney, L., & Lindenmayer, D. B. (2023). The characteristics of regeneration failure and their potential to shift wet temperate forests into alternate stable states. *Forest Ecology and Management*, *529*. https://doi.org/10.1016/j.foreco.2022.120673
11. Bowman, D., Kolden, C. A., Abatzoglou, J. T., Johnston, F. H., van der Werf, G. R., & Flannigan, M. (2020). Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment*, *1*(10), 500–515. https://doi.org/10.1038/s43017-020-0085-3
12. Bowman, D. M. J. S., Moreira-Muñoz, A., Kolden, C. A., Chávez, R. O., Muñoz, A. A., Salinas, F., González-Reyes, Á., Rocco, R., De La Barrera, F., Williamson, G. J., Borchers, N., Cifuentes, L. A., Abatzoglou, J. T., & Johnston, F. H. (2019). Human–environmental drivers and impacts of the globally extreme 2017 Chilean fires. *Ambio*, *48*(4), 350–362. https://doi.org/10.1007/s13280-018-1084-1
13. Brown, T. P., Inbar, A., Duff, T. J., Burton, Jamie. E., Noske, P. J., Lane, P. N. J., & Sheridan, G. J. (2021). Forest structure drives fuel moisture response across alternative forest states. *Fire*, *4*(48). https://doi.org/10.3390/fire4030048
14. Burton, J. E., Cawson, J. G., Filkov, A. I., Penman, T. D., & Cornelissen, H. (2020). Leaf traits predict global patterns in the structure and flammability of forest litter beds. *Journal of Ecology*, *109*(3), 1344–1355. https://doi.org/10.1111/1365-2745.13561
15. Burton, J. E., Cawson, J., Noske, P., & Sheridan, G. (2019). Shifting states, altered fates: Divergent fuel moisture responses after high frequency wildfire in an obligate seeder eucalypt forest. *Forests*, *10*(5), 436. https://doi.org/https://doi.org/10.3390/f10050436
16. Burton, J. E., Filkov, A. I., Pickering, B. J., Penman, T. D., & Cawson, J. G. (2023)a. Quantifying Litter Bed Ignitability: Comparison of a Laboratory and Field Method. *Fire*, *6*(1), 24. https://doi.org/10.3390/fire6010024
17. Burton, J. E., Penman, T. D., Filkov, A. I., & Cawson, J. G. (2023)b. Multi-scale investigation of factors influencing moisture thresholds for litter bed flammability. *Agricultural and Forest Meteorology*, *337*, 109514. https://doi.org/10.1016/j.agrformet.2023.109514
18. Cawson, J. G., Burton, J. E., Pickering, B. J., & Penman, T. D. (2024). Moisture thresholds for ignition vary between types of eucalypt forests across an aridity gradient. *Landscape Ecology*, *39*(3), 70. https://doi.org/10.1007/s10980-024-01864-6
19. Cawson, J. G., Duff, T. J., Swan, M. H., & Penman, T. D. (2018). Wildfire in wet sclerophyll forests: The interplay between disturbances and fuel dynamics. *Ecosphere*, *9*(5), e02211. https://doi.org/10.1002/ecs2.2211
20. Cawson, J. G., Pickering, B. J., Filkov, A. I., Burton, J. E., Kilinc, M., & Penman, T. D. (2022). Predicting ignitability from firebrands in mature wet eucalypt forests. *Forest Ecology and Management*, *519*, 120315. https://doi.org/10.1016/j.foreco.2022.120315
21. Cawson, J. G., Pickering, B., Penman, T. D., & Filkov, A. (2021). Quantifying the effect of mastication on flaming and smouldering durations in eucalypt forests and woodlands under laboratory conditions. *International Journal of Wildland Fire*, *30*(8), 611–624. https://doi.org/10.1071/WF20157
22. Cheal, D. (2010). *Growth stages and tolerable fire intervals for Victoria's native vegetation data sets* (Fire and Adaptive Management Report No. 84; Fire and Adaptive Management Report). Department of Sustainability and Environment.
23. Cheney, N. P., Gould, J. S., McCaw, W. L., & Anderson, W. R. (2012). Predicting fire behaviour in dry eucalypt forest in southern Australia. *Forest Ecology and Management*, *280*, 120–131. https://doi.org/10.1016/j.foreco.2012.06.012
24. Cheng, L., Tang, Q., Xu, Z., & Sucharitakul, P. (2025). Alternative biome states in Australian terrestrial ecosystems and the potential maintenance mechanism. *Ecological Frontiers*, *45*(3), 658–666. https://doi.org/10.1016/j.ecofro.2025.01.005
25. Collins, L., Bradstock, R. A., Clarke, H., Clarke, M. F., Nolan, R. H., & Penman, T. D. (2021). The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity fire. *Environmental Research Letters*, *16*(4), 044029. https://doi.org/10.1088/1748-9326/abeb9e
26. Collins, L., Trouvé, R., Baker, P. J., Cirulus, B., Nitschke, C. R., Nolan, R. H., Smith, L., & Penman, T. D. (2023). Fuel reduction burning reduces wildfire severity during extreme fire events in south-eastern Australia. *Journal of Environmental Management*, *343*, 118171. https://doi.org/10.1016/j.jenvman.2023.118171
27. Coop, J. D., Parks, S. A., Stevens-Rumann, C. S., Crausbay, S. D., Higuera, P. E., Hurteau, M. D., Tepley, A., Whitman, E., Assal, T., Collins, B. M., Davis, K. T., Dobrowski, S., Falk, D. A., Fornwalt, P. J., Fule, P. Z., Harvey, B. J., Kane, V. R., Littlefield, C. E., Margolis, E. Q., … Rodman, K. C. (2020). Wildfire-

driven forest conversion in western North American landscapes. *Bioscience*, *70*(8), 659–673. https://doi.org/10.1093/biosci/biaa061

28. Costermans, L. F. (2009). *Native trees and shrubs of south-eastern Australia* ([New ed.]). Reed New Holland.
29. Cruz, M. G. (2021). *The Vesta Mk 2 rate of fires spread model: A users guide*. CSIRO.
30. Cruz, M. G., Cheney, N. P., Gould, J. S., McCaw, W. L., Kilinc, M., & Sullivan, A. L. (2022). An empirical-based model for predicting the forward spread rate of wildfires in eucalypt forests. *International Journal of Wildland Fire*, *31*(1), 81–95. https://doi.org/10.1071/WF21068
31. Cruz, M. G., Gould, J. S., Alexander, M. E., Sullivan, A. L., McCaw, L., & Matthews, S. (2015). *Guide to fire spread models for Australian vegetation.* CSIRO Land and Water, Canberra, ACT, and AFAC, Melbourne, Vic.
32. Davies, J. B., & Oates, A. M. (1999). *Ecological Vegetation Class (EVC) mapping of Wilsons Promontory and adjacent islands*. Department of Natural Resources and Environment.
33. DEECAa (Department of Energy Environment and Climate Action). (2025). *Bioregions and EVC benchmarks*. Bioregions and EVC Benchmarks. https://www.environment.vic.gov.au/biodiversity/bioregions-and-evc-benchmarks
34. DEECAb (Department of Energy Environment and Climate Action). (2021). *Fire History Records of Fires across Victoria*.
35. Dowdy, A. J., Fromm, M. D., & McCarthy, N. (2017). Pyrocumulonimbus lightning and fire ignition on Black Saturday in southeast Australia. *Journal of Geophysical Research: Atmospheres*, *122*(14), 7342–7354. https://doi.org/10.1002/2017JD026577
36. Dwomoh, F. K., & Wimberly, M. C. (2017). Fire regimes and forest resilience: Alternative vegetation states in the West African tropics. *Landscape Ecology*, *32*(9), 1849–1865. https://doi.org/10.1007/s10980-017-0553-4
37. Ellis, P. F. M. (2011). Fuelbed ignition potential and bark morphology explain the notoriety of the eucalypt messmate 'stringybark' for intense spotting. *International Journal of Wildland Fire*, *20*(7), 897–907. https://doi.org/10.1071/WF10052
38. Engber, E. A., & Varner, J. M. (2012). Patterns of flammability of the California oaks: The role of leaf traits. *Canadian Journal of Forest Research*, *42*(11), 1965–1975. https://doi.org/10.1139/x2012-138
39. Fairman, T. A., Bennett, L. T., & Nitschke, C. R. (2019). Short-interval wildfires increase likelihood of resprouting failure in fire-tolerant trees. *Journal of Environmental Management*, *231*, 59–65. https://doi.org/10.1016/j.jenvman.2018.10.021
40. Fairman, T. A., Symon, C., Cawson, J., & Penman, T. D. (2024). Throwing fuel on the fire? Contrasting fine and coarse fuel responses to windthrow in temperate eucalypt forests in south-eastern Australia. *Forest Ecology and Management*, *572*, 122266. https://doi.org/10.1016/j.foreco.2024.122266
41. Falk, D. A., van Mantgem, P. J., Keeley, J. E., Gregg, R. M., Guiterman, C. H., Tepley, A. J., Jn Young, D., & Marshall, L. A. (2022). Mechanisms of forest resilience. *Forest Ecology and Management*, *512*. https://doi.org/10.1016/j.foreco.2022.120129
42. Fernández-Guisuraga, J. M., & Calvo, L. (2025). Fire severity shows limited dependence on fuel structure under adverse fire weather conditions: A case study of two extreme wildfire events. *Fire Ecology*, *21*(1), 28. https://doi.org/10.1186/s42408-025-00371-6
43. Fox, B. J., Fox, M. D., & McKay, G. M. (1979). Litter accumulation after fire in a Eucalypt forest. *Australian Journal of Botany*, *27*(2), 157–165. https://doi.org/10.1071/BT9790157
44. Ganteaume, A., Lampin-Maillet, C., Guijarro, M., Hernando, C., Jappiot, M., Fonturbel, T., Pérez-Gorostiaga, P., & Vega, J. A. (2009). Spot fires: Fuel bed flammability and capability of firebrands to ignite fuel beds. *International Journal of Wildland Fire*, *18*(8), 951–969. https://doi.org/10.1071/WF07111
45. Gibson, R., Danaher, T., Hehir, W., & Collins, L. (2020). A remote sensing approach to mapping fire severity in south-eastern Australia using sentinel 2 and random forest. *Remote Sensing of Environment*, *240*, 111702. https://doi.org/10.1016/j.rse.2020.111702
46. Gill, A. M. (1975). Fire and the Australian flora: A review. *Australian Forestry*, *38*(1), 4–25. https://doi.org/10.1080/00049158.1975.10675618
47. Google Maps. (n.d.). *Satellite imagery of Wilsons Promontroy National Park*.
48. Gordon, C. E., Nolan, R. H., Boer, M. M., Bendall, E. R., Williamson, J. S., Price, O. F., Kenny, B. J., Taylor, J. E., Denham, A. J., & Bradstock, R. A. (2024). Severe and Short Interval Fires Rearrange Dry Forest Fuel Arrays in South-Eastern Australia. *Fire*, *7*(4), 130. https://doi.org/10.3390/fire7040130
49. Gould, J. S., McCaw, W., Cheney, N., Ellis, P. F., Knight, I., & Sullivan, A. L. (2008). *Project Vesta: Fire in dry eucalypt forest: Fuel structure, fuel dynamics and fire behaviour*. CSIRO Publishing.
50. Grootemaat, S., Wright, I. J., Van Bodegom, P. M., Cornelissen, J. H. C., & Cornwell, W. K. (2015). Burn or rot: Leaf traits explain why flammability and decomposability are decoupled across species. *Functional Ecology*, *29*(11), 1486–1497. https://doi.org/10.1111/1365-2435.12449
51. Guiterman, C. H., Margolis, E. Q., Allen, C. D., Falk, D. A., & Swetnam, T. W. (2018). Long-Term Persistence and Fire Resilience of Oak Shrubfields in Dry Conifer Forests of Northern New Mexico. *Ecosystems*, *21*(5), 943–959. https://doi.org/10.1007/s10021-017-0192-2
52. Harmon, M. E., Franklin, J. F., Swanson, F. J., Sollins, P., Gregory, S., Lattin, J., Anderson, N., Cline, S., Aumen, N. G., & Sedell, J. (1986). Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research*, *15*, 133–302. https://doi.org/10.1016/S0065-2504(08)60121-X
53. Heap, A. E., Fairman, T. A., Penman, T. D., & Bennett, L. T. (2026). Characterising Ecosystem Composition, Structure and Function of Alternative Stable States in Temperate Forests of South-Eastern Australia. *Global Change Biology*, *32*(5), e70895. https://doi.org/10.1111/gcb.70895
54. Heap, A. E., Penman, T. D., Bennett, L. T., & Fairman, T. A. (2025). Short-interval fires homogenise the structure of diverse temperate forests. *Forest Ecology and Management*, *584*, 122580. https://doi.org/10.1016/j.foreco.2025.122580

55. Hines, F., Tolhurst, K. G., Wilson, A. G., & McCarthy, G. J. (2010). *Overall fuel hazard assessment guide: Fire and adaptive management report no.82* (Department of Sustainability and Environment Melbourne, Trans.; No. 82; p. 41). Victorian Government Department of Sustainability and Environment Melbourne.

56. Hirota, M., Holmgren, M., Van Nes, E. H., & Scheffer, M. (2011). Global resilience of tropical forest and savanna to critical transitions. *Science*, *334*(6053), 232–235. https://doi.org/10.1126/science.1210657

57. Hodgson, A. (1967, March). Fire management in eucalypt forest. *6th Annual Tall Timbers Fire Ecology Conference*. Fire Ecology Conference.

58. Hollis, J. J., Cruz, M. G., McCaw, W. L., Gould, J. S., & Samson, S. A. (2025). An efficient and comprehensive field protocol for assessing fuel characteristics for fire behaviour modelling in Australian open forests. *MethodsX*, *14*, 103345. https://doi.org/10.1016/j.mex.2025.103345

59. Hollis, J. J., McCaw, W. L., & Cruz, M. G. (2018). The effect of woody fuel characteristics on fuel ignition and consumption: A case study from a eucalypt forest in south-west Western Australia. *International Journal of Wildland Fire*, *27*(5), 363. https://doi.org/10.1071/WF17174

60. Hyde, J. C., Smith, A. M. S., Ottmar, R. D., Alvarado, E. C., & Morgan, P. (2011). The combustion of sound and rotten coarse woody debris: A review. *International Journal of Wildland Fire*, *20*(2), 163–174. https://doi.org/10.1071/WF09113

61. Kirchmeier-Young, M. C., Gillett, N. P., Zwiers, F. W., Cannon, A. J., & Anslow, F. S. (2019). Attribution of the Influence of Human-Induced Climate Change on an Extreme Fire Season. *Earth's Future*, *7*(1), 2–10. https://doi.org/10.1029/2018EF001050

62. Knox, K. J. E., & Clarke, P. J. (2012). Fire severity, feedback effects and resilience to alternative community states in forest assemblages. *Forest Ecology and Management*, *265*, 47–54. https://doi.org/10.1016/j.foreco.2011.10.025

63. Koo, E., Pagni, P. J., Weise, D. R., & Woycheese, J. P. (2010). Firebrands and spotting ignition in large-scale fires. *International Journal of Wildland Fire*, *19*(7), 818–843. https://doi.org/10.1071/WF07119

64. Krebs, P., Pezzatti, G. B., Mazzoleni, S., Talbot, L. M., & Conedera, M. (2010). Fire regime: History and definition of a key concept in disturbance ecology. *Theory in Biosciences*, *129*(1), 53–69. https://doi.org/10.1007/s12064-010-0082-z

65. Kreye, J. K., Varner, J. M., Hamby, G. W., & Kane, J. M. (2018). Mesophytic litter dampens flammability in fire-excluded pyrophytic oak–hickory woodlands. *Ecosphere*, *9*(1), e02078. https://doi.org/10.1002/ecs2.2078

66. Lindenmayer, D. B., Hobbs, R. J., Likens, G. E., Krebs, C. J., & Banks, S. C. (2011). Newly discovered landscape traps produce regime shifts in wet forests. *Proceedings of the National Academy of Sciences*, *108*(38), 15887–15891. https://doi.org/10.1073/pnas.1110245108

67. Loudermilk, E. L., O'Brien, J. J., Goodrick, S. L., Linn, R. R., Skowronski, N. S., & Hiers, J. K. (2022). Vegetation's influence on fire behavior goes beyond just being fuel. *Fire Ecology*, *18*(1), 9, s42408-022-00132–00139. https://doi.org/10.1186/s42408-022-00132-9

68. Luo, C., Shen, Z., Wang, X., Xiahou, M., Xie, Y., Yang, T., & Pausas, J. (2025). The effects of fire frequency on leaf and bark flammability strategies in subtropical semi-humid evergreen broadleaved forests in China. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *380 1924*, 20230462. https://doi.org/10.1098/rstb.2023.0462

69. Marshall, E., Holyland, B., Parkins, K., Raulings, E., Good, M. K., Swan, M., Bennett, L. T., & Penman, T. D. (2024). Can green firebreaks help balance biodiversity, carbon storage and wildfire risk? *Journal of Environmental Management*, *369*, 122183. https://doi.org/10.1016/j.jenvman.2024.122183

70. McArthur, A. G. (1967). *Fire behaviour in eucalypt forests*. Australia. Forestry and Timber Bureau.

71. McArthur, A. G., & Cheney, N. P. (2015). The Characterization of Fires in Relation to Ecological Studies. *Fire Ecology*, *11*(1), 3–9. https://doi.org/10.1007/BF03400629

72. McColl-Gausden, S., Bennett, L. T., Clarke, H., & Penman, T. D. (2025). Fuelling future fires: Predicting variation in fuel hazard and availability across an environmental gradient. *International Journal of Wildland Fire*, *34*(7). https://doi.org/10.1071/WF24222

73. McColl-Gausden, S. C., Bennett, L. T., Ababei, D. A., Clarke, H. G., Penman, T. D., & Archibald, S. (2021). Future fire regimes increase risks to obligate-seeder forests. *Diversity and Distributions*, *28*(3), 542–558. https://doi.org/10.1111/ddi.13417

74. McColl-Gausden, S. C., Bennett, L. T., Duff, T. J., Cawson, J. G., & Penman, T. D. (2020). Climatic and edaphic gradients predict variation in wildland fuel hazard in south-eastern Australia. *Ecography*, *43*(3), 443–455. https://doi.org/10.1111/ecog.04714

75. McDowell, N. G., Allen, C. D., Anderson-Teixeira, K., Aukema, B. H., Bond-Lamberty, B., Chini, L., Clark, J. S., Dietze, M., Grossiord, C., Hanbury-Brown, A., Hurtt, G. C., Jackson, R. B., Johnson, D. J., Kueppers, L., Lichstein, J. W., Ogle, K., Poulter, B., Pugh, T. A. M., Seidl, R., … Xu, C. (2020). Pervasive shifts in forest dynamics in a changing world. *Science*, *368*(6494), eaaz9463. https://doi.org/10.1126/science.aaz9463

76. McLauchlan, K. K., Higuera, P. E., Miesel, J., Rogers, B. M., Schweitzer, J., Shuman, J. K., Tepley, A. J., Varner, J. M., Veblen, T. T., Adalsteinsson, S. A., Balch, J. K., Baker, P., Batllori, E., Bigio, E., Brando, P., Cattau, M., Chipman, M. L., Coen, J., Crandall, R., … Watts, A. C. (2020). Fire as a fundamental ecological process: Research advances and frontiers. *Journal of Ecology*, *108*(5), 2047–2069. https://doi.org/10.1111/1365-2745.13403

77. Mihajlovski, B., Fernandes, P. M., Pereira, J. M. C., & Guerra-Hernández, J. (2023). Comparing Forest Understory Fuel Classification in Portugal Using Discrete Airborne Laser Scanning Data and Satellite Multi-Source Remote Sensing Data. *Fire*, *6*(9), 327. https://doi.org/10.3390/fire6090327

78. Murphy, B. P., Bradstock, R. A., Boer, M. M., Carter, J., Cary, G. J., Cochrane, M. A., Fensham, R. J., Russell-Smith, J., Williamson, G. J., Bowman, D. M. J. S., & Ladiges, P. (2013). Fire regimes of Australia: A pyrogeographic model system. *Journal of Biogeography*, *40*(6), 1048–1058. https://doi.org/10.1111/jbi.12065

79. Noble, I. R., Gill, A. M., & Bary, G. A. V. (1980). McArthur's fire-danger meters expressed as equations. *Australian Journal of Ecology*, *5*(2), 201–203.

80. Nolan, R. H., Boer, M. M., Collins, L., Resco De Dios, V., Clarke, H., Jenkins, M., Kenny, B., & Bradstock, R. A. (2020). Causes and consequences of eastern Australia's 2019–20 season of mega-fires. *Global Change Biology*, *26*(3), 1039–1041. https://doi.org/10.1111/gcb.14987

81. Nolan, R. H., Collins, L., Leigh, A., Ooi, M. K. J., Curran, T. J., Fairman, T. A., Resco de Dios, V., & Bradstock, R. (2021). Limits to post-fire vegetation recovery under climate change. *Plant, Cell & Environment*, *44*(11), 3471–3489. https://doi.org/10.1111/pce.14176
82. Nolan, R. H., Gibson, R. K., Cirulis, B., Holyland, B., Samson, S. A., Jenkins, M., Penman, T., & Boer, M. M. (2024). Incorporating burn heterogeneity with fuel load estimates may improve fire behaviour predictions in south-east Australian eucalypt forest. *International Journal of Wildland Fire*, *33*(3), WF22179. https://doi.org/10.1071/WF22179
83. Ottmar, R. D., Sandberg, D. V., Riccardi, C. L., & Prichard, S. J. (2007). An overview of the Fuel Characteristic Classification System—Quantifying, classifying, and creating fuelbeds for resource planningThis article is one of a selection of papers published in the Special Forum on the Fuel Characteristic Classification System. *Canadian Journal of Forest Research*, *37*(12), 2383–2393. https://doi.org/10.1139/X07-077
84. Paritsis, J., Veblen, T. T., & Holz, A. (2015). Positive fire feedbacks contribute to shifts from Nothofagus pumilio forests to fire-prone shrublands in Patagonia. *Journal of Vegetation Science*, *26*(1), 89–101. https://doi.org/10.1111/jvs.12225
85. Pausas, J. G., & Bond, W. J. (2020). Alternative Biome States in Terrestrial Ecosystems. *Trends in Plant Science*, *25*(3), 250–263. https://doi.org/10.1016/j.tplants.2019.11.003
86. Penman, T. E., Cawson, J. G., Murphy, S., & Duff, T. J. (2017). Messmate stringybark: Bark ignitability and burning sustainability in relation to fragment dimensions, hazard score and time since fire. *International Journal of Wildland Fire*, *26*(10), 866–876. https://doi.org/10.1071/WF16146
87. Pickering, B. J., Bennett, L. T., & Cawson, J. G. (2023). Extending methods for assessing fuel hazard in temperate Australia to enhance data quality and consistency. *International Journal of Wildland Fire*, *32*(10), 1422–1437. https://doi.org/10.1071/WF22219
88. Pickering, B. J., Kultaev, D., Holyland, B., Ababei, D., & Penman, T. D. (2025). The changing risk of fire to human and environmental assets under climate induced altered fire regimes in south-east Australia. *International Journal of Disaster Risk Reduction*, *127*, 105668. https://doi.org/10.1016/j.ijdrr.2025.105668
89. Plucinski, M. P., & Anderson, W. R. (2008). Laboratory determination of factors influencing successful point ignition in the litter layer of shrubland vegetation. *International Journal of Wildland Fire*, *17*(5), 628. https://doi.org/10.1071/WF07046
90. Plumanns-Pouton, E., McColl-Gausden, S. C., Collins, L., Harvey, B. J., & Krawchuk, M. A. (2025). Fire in focus: Clarifying metrics and terminology for better ecological insight. *Journal of Applied Ecology*.
91. Ramírez, D. P., Estay, S. A., Miranda, A., G. Pausas, J., & Paula, S. (2025). Fire-driven alternative vegetation states across the temperate Andes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *380*(1924), 20230509. https://doi.org/10.1098/rstb.2023.0509
92. Scarff, F. R., & Westoby, M. (2006). Leaf litter flammability in some semi-arid Australian woodlands. *Functional Ecology*, *20*(5), 745–752. https://doi.org/10.1111/j.1365-2435.2006.01174.x
93. Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591–596. https://doi.org/10.1038/35098000
94. Schwilk, D. W., & Caprio, A. C. (2011). Scaling from leaf traits to fire behaviour: Community composition predicts fire severity in a temperate forest: Leaf length and fire behaviour. *Journal of Ecology*, *99*(4), 970–980. https://doi.org/10.1111/j.1365-2745.2011.01828.x
95. Schwörer, C., Morales-Molino, C., Gobet, E., Henne, P. D., Pasta, S., Pedrotta, T., Van Leeuwen, J. F. N., Vannière, B., & Tinner, W. (2024). Simulating past and future fire impacts on Mediterranean ecosystems. *Journal of Ecology*, *112*(5), 954–970. https://doi.org/10.1111/1365-2745.14293
96. Steel, Z. L., Foster, D., Coppoletta, M., Lydersen, J. M., Stephens, S. L., Paudel, A., Markwith, S. H., Merriam, K., & Collins, B. M. (2021). Ecological resilience and vegetation transition in the face of two successive large wildfires. *Journal of Ecology*, *109*(9), 3340–3355. https://doi.org/10.1111/1365-2745.13764
97. Su, C.-H., Rennie, S., Torrance, J., Howard, E., Stassen, C., Lipson, M., Warren, R., Pepler, A., Dharssi, I., & Franklin, C. (2024). *BARRA-C2: Development of the kilometre-scale downscaled atmospheric reanalysis over Australia*. Australian Bureau of Meteorology.
98. Sullivan, A. L., Surawski, N. C., Crawford, D., Hurley, R. J., Volkova, L., Weston, C. J., & Meyer, C. P. (2018). Effect of woody debris on the rate of spread of surface fires in forest fuels in a combustion wind tunnel. *Forest Ecology and Management*, *424*, 236–245. https://doi.org/10.1016/j.foreco.2018.04.039
99. Taylor, S. W., Alexander, M. E., & Pike, R. (1997). *Field guide to the Canadian forest fire behavior prediction (FBP) system* (Vol. 11). Canadian Forest Service, Northern Forestry Centre Edmonton, Alberta, Canada.
100. Tepley, A. J., Thomann, E., Veblen, T. T., Perry, G. L. W., Holz, A., Paritsis, J., Kitzberger, T., & Anderson-Teixeira, K. J. (2018). Influences of fire–vegetation feedbacks and post-fire recovery rates on forest landscape vulnerability to altered fire regimes. *Journal of Ecology*, *106*(5), 1925–1940. https://doi.org/10.1111/1365-2745.12950
101. Thomsen, A. M., Lemmon, J., Allen, V., Mills, C. H., Keith, D. A., & Ooi, M. K. J. (2025). Evidence for state shift and generation of fire feedback loops in mesic forest driven by extreme fire severity and high fire frequency. *Environmental Research Letters*, *20*(4), 044021. https://doi.org/10.1088/1748-9326/adbf30
102. Thurston, W., Tory, K. J., Fawcett, R. J., & Kepert, J. D. (2016). *Large-eddy simulations of pyroconvection and its sensitivity to moisture*. 5th International Fire Behaviour and Fuels Conference proceedings.
103. Tiribelli, F., Kitzberger, T., & Morales, J. M. (2018). Changes in vegetation structure and fuel characteristics along post-fire succession promote alternative stable states and positive fire–vegetation feedbacks. *Journal of Vegetation Science*, *29*(2), 147–156. https://doi.org/10.1111/jvs.12620

104. Turco, M., Jerez, S., Augusto, S., Tarin-Carrasco, P., Ratola, N., Jimenez-Guerrero, P., & Trigo, R. M. (2019). Climate drivers of the 2017 devastating fires in Portugal. *Scientific Reports*, *9*(1), 13886. https://doi.org/10.1038/s41598-019-50281-2

105. Turnbull, C. R. A., & Madden, J. L. (1983). Relationship of litterfall to basal area and climatic variables in cool temperate forests of southern Tasmania. *Australian Journal of Ecology*, *8*(4), 425–431. https://doi.org/10.1111/j.1442-9993.1983.tb01339.x

106. Van Wagner, C. E. (1968). The line intersect method in forest fuel sampling. *Forest Science*, *14*(1), 20–26. https://doi.org/10.1093/forestscience/14.1.20

107. Van Wagner, C. E. (1977). Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research*, *7*(1), 23–34. https://doi.org/10.1139/x77-004

108. Wang, B., Spessa, A. C., Feng, P., Hou, X., Yue, C., Luo, J.-J., Ciais, P., Waters, C., Cowie, A., Nolan, R. H., Nikonovas, T., Jin, H., Walshaw, H., Wei, J., Guo, X., Liu, D. L., & Yu, Q. (2022). Extreme fire weather is the major driver of severe bushfires in southeast Australia. *Science Bulletin*, *67*(6), 655–664. https://doi.org/10.1016/j.scib.2021.10.001

109. Wei, P., Lamont, B., He, T., Xue, W., Wang, P. C., Song, W., Zhang, R., Keyhani, A. B., Zhao, S., Lu, W., Dong, F., Gao, R., Yu, J., Huang, Y., Tang, L., Lu, K., Ma, J., Xiong, Z., Chen, L., … Yan, Z. (2024). Vegetation–fire feedbacks increase subtropical wildfire risk in scrubland and reduce it in forests. *Journal of Environmental Management*, *351*, 119726. https://doi.org/10.1016/j.jenvman.2023.119726

110. Whelan, R. J. (1995). *The ecology of fire*. Cambridge university press.

111. Whitman, E., Parks, S. A., Holsinger, L. M., & Parisien, M.-A. (2022). Climate-induced fire regime amplification in Alberta, Canada. *Environmental Research Letters*, *17*(5). https://doi.org/10.1088/1748-9326/ac60d6

112. Williams, A. P., Abatzoglou, J. T., Gershunov, A., Guzman-Morales, J., Bishop, D. A., Balch, J. K., & Lettenmaier, D. P. (2019). Observed Impacts of Anthropogenic Climate Change on Wildfire in California. *Earth's Future*, *7*(8), 892–910. https://doi.org/10.1029/2019EF001210

113. Woldendorp, G., & Keenan, R. J. (2005). Coarse woody debris in Australian forest ecosystems: A review. *Austral Ecology*, *30*(8), 834–843. https://doi.org/10.1111/j.1442-9993.2005.01526.x

114. Zhao, L., Yebra, M., Van Dijk, A. I. J. M., Cary, G. J., Matthews, S., & Sheridan, G. (2021). The influence of soil moisture on surface and sub-surface litter fuel moisture simulation at five Australian sites. *Agricultural and Forest Meteorology*, *298–299*, 108282. https://doi.org/10.1016/j.agrformet.2020.108282

115. Zylstra, P., Bradstock, R. A., Bedward, M., Penman, T. D., Doherty, M. D., Weber, R. O., Gill, A. M., & Cary, G. J. (2016). Biophysical Mechanistic Modelling Quantifies the Effects of Plant Traits on Fire Severity: Species, Not Surface Fuel Loads, Determine Flame Dimensions in Eucalypt Forests. *PLoS One*, *11*(8), e0160715. https://doi.org/10.1371/journal.pone.0160715

116. Zylstra, P. J., & Lindenmayer, D. B. (2025). Are the alternative ecosystem states produced by positive fire-flammability feedbacks reversible? *Environmental Research Letters*, *20*(12), 124037. https://doi.org/10.1088/1748-9326/ae18e7

Figures

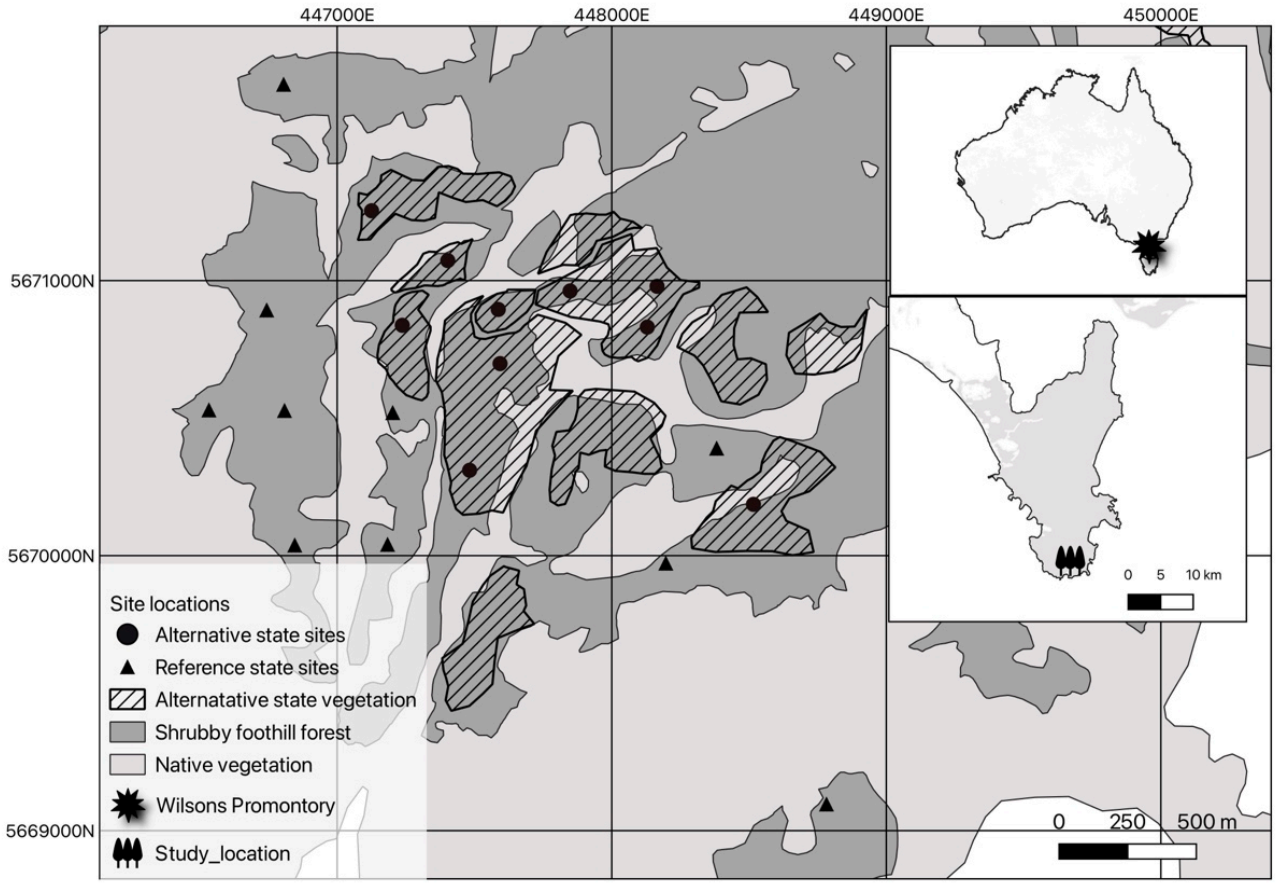


Figure 1

Location of study sites within Wilsons Promontory National Park. Eucalypt-dominated Shrubby Foothill Forest is shown in dark grey within the broader native vegetation matrix (light grey). Areas transitioned to alternative states in the mid-1900s are indicated by cross-hatched polygons originally mapped by Davies and Oates (1999) and refined by Heap et al. (2025) using satellite imagery (Google Maps, n.d.). Plot locations are shown as reference plots (triangles) and alternative plots (circles).

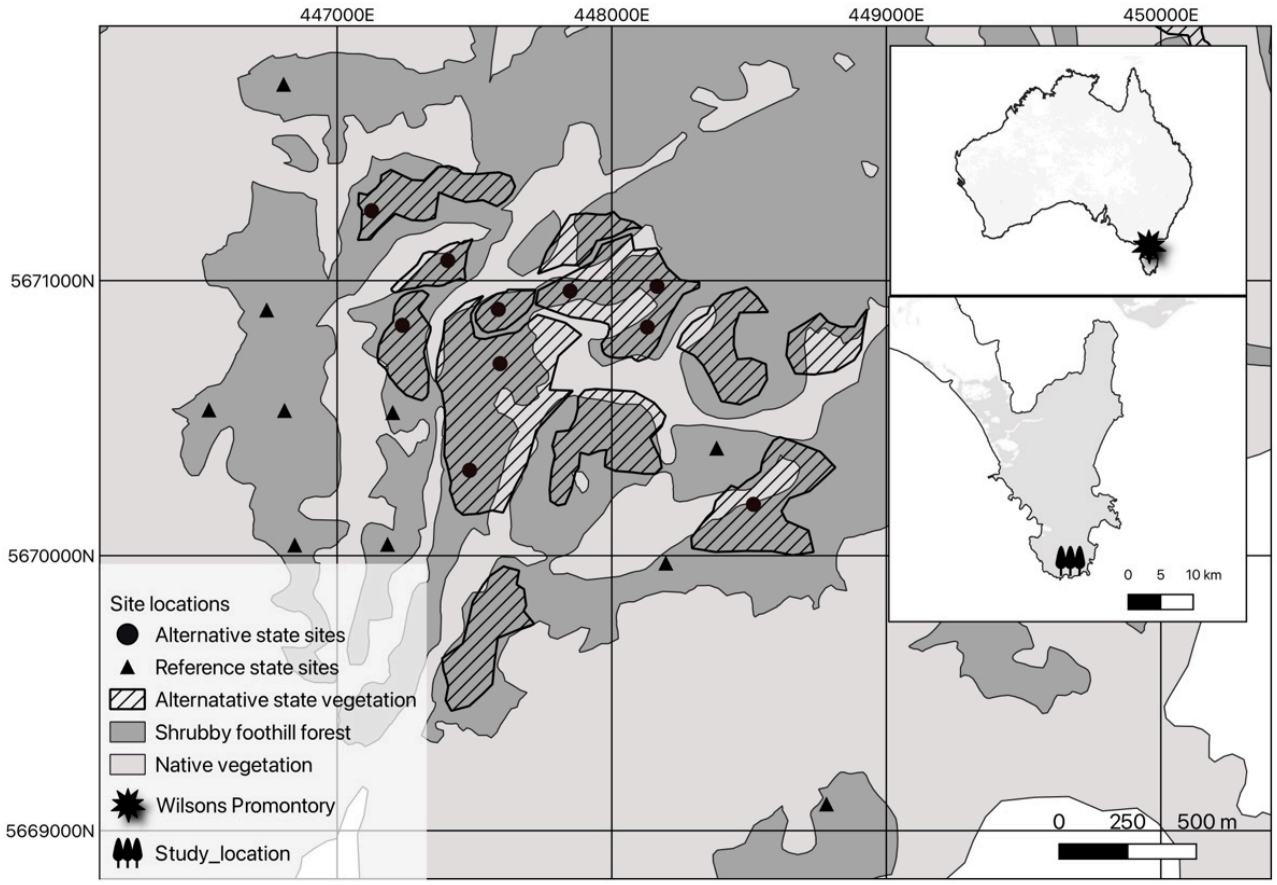


Figure 1

Location of study sites within Wilsons Promontory National Park. Eucalypt-dominated Shrubby Foothill Forest is shown in dark grey within the broader native vegetation matrix (light grey). Areas transitioned to alternative states in the mid-1900s are indicated by cross-hatched polygons originally mapped by Davies and Oates (1999) and refined by Heap et al. (2025) using satellite imagery (Google Maps, n.d.). Plot locations are shown as reference plots (triangles) and alternative plots (circles).

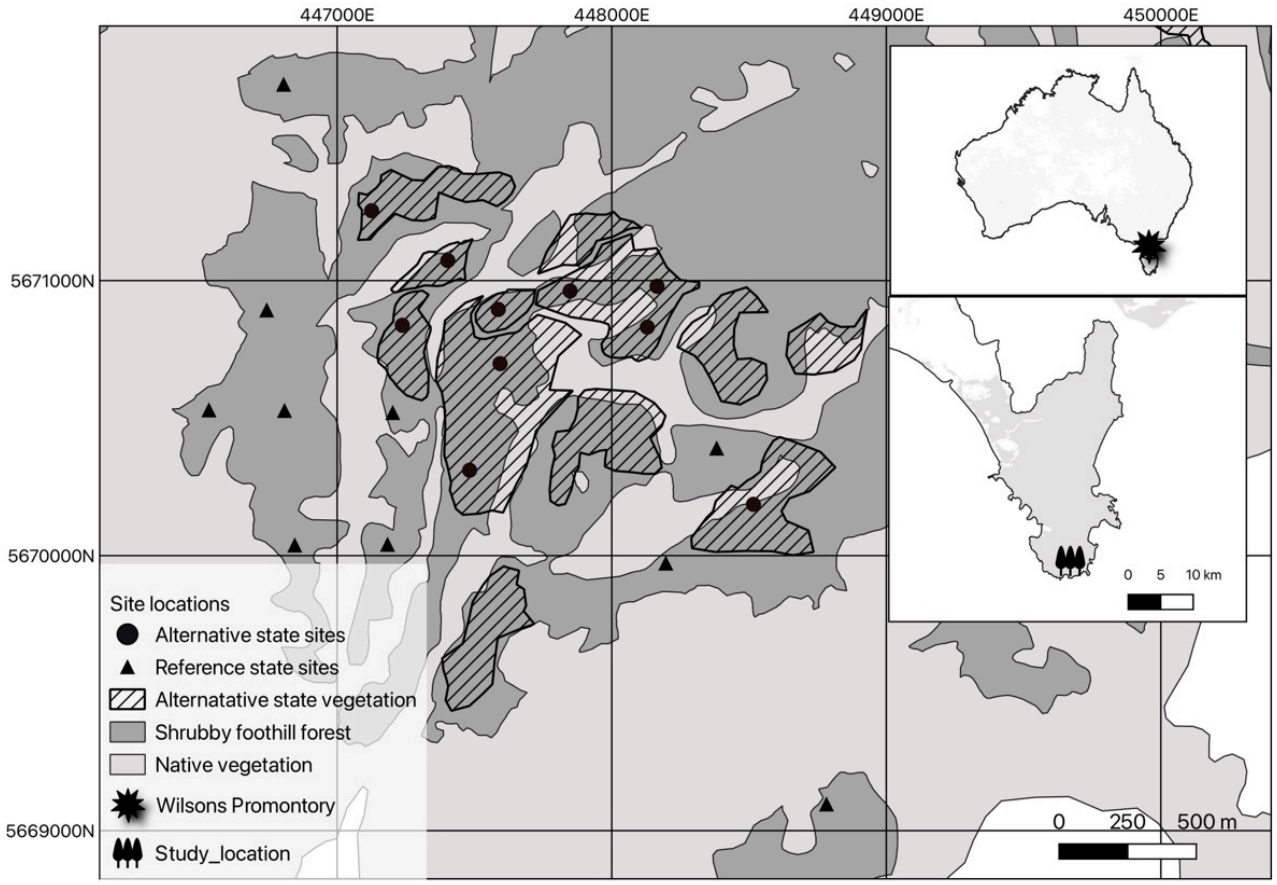


Figure 1

Location of study sites within Wilsons Promontory National Park. Eucalypt-dominated Shrubby Foothill Forest is shown in dark grey within the broader native vegetation matrix (light grey). Areas transitioned to alternative states in the mid-1900s are indicated by cross-hatched polygons originally mapped by Davies and Oates (1999) and refined by Heap et al. (2025) using satellite imagery (Google Maps, n.d.). Plot locations are shown as reference plots (triangles) and alternative plots (circles).

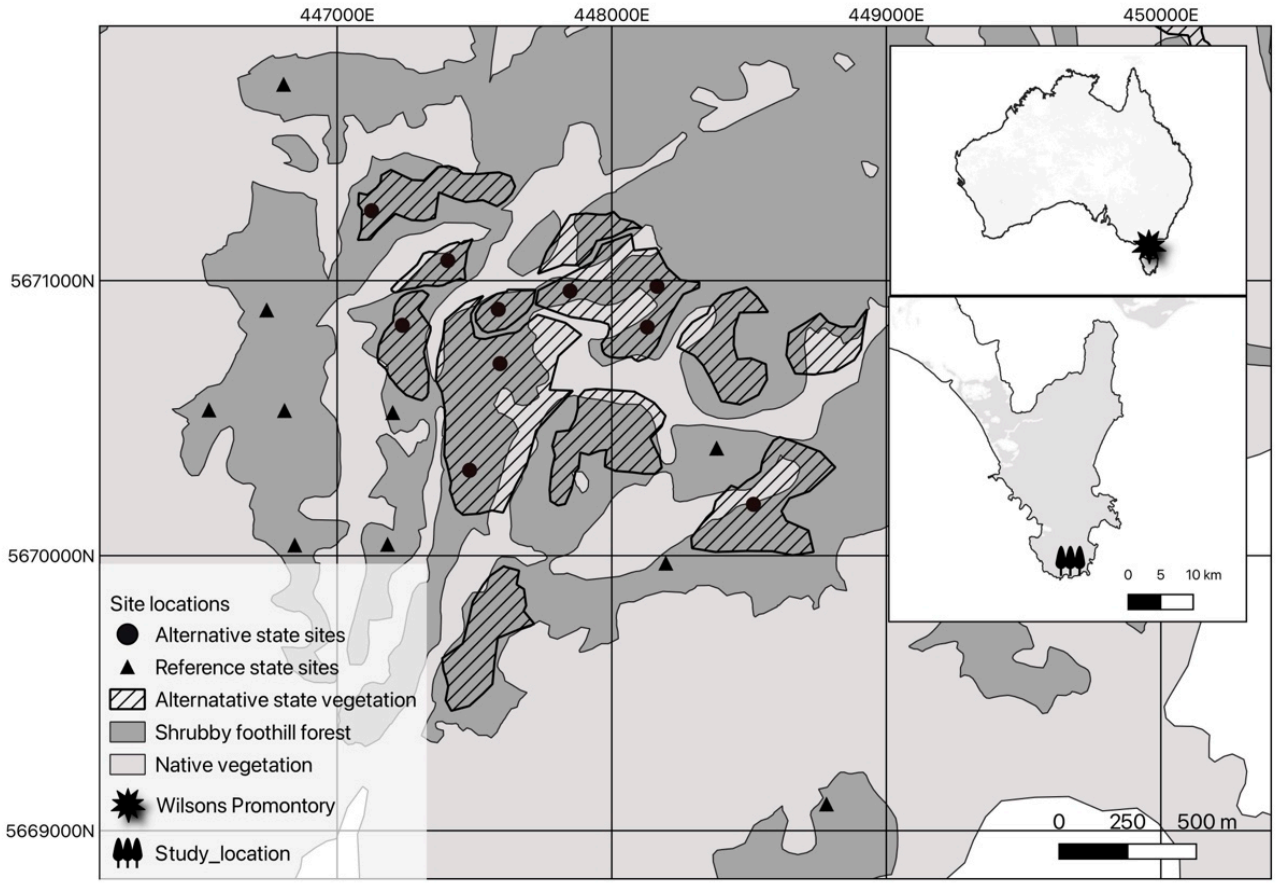


Figure 1

Location of study sites within Wilsons Promontory National Park. Eucalypt-dominated Shrubby Foothill Forest is shown in dark grey within the broader native vegetation matrix (light grey). Areas transitioned to alternative states in the mid-1900s are indicated by cross-hatched polygons originally mapped by Davies and Oates (1999) and refined by Heap et al. (2025) using satellite imagery (Google Maps, n.d.). Plot locations are shown as reference plots (triangles) and alternative plots (circles).

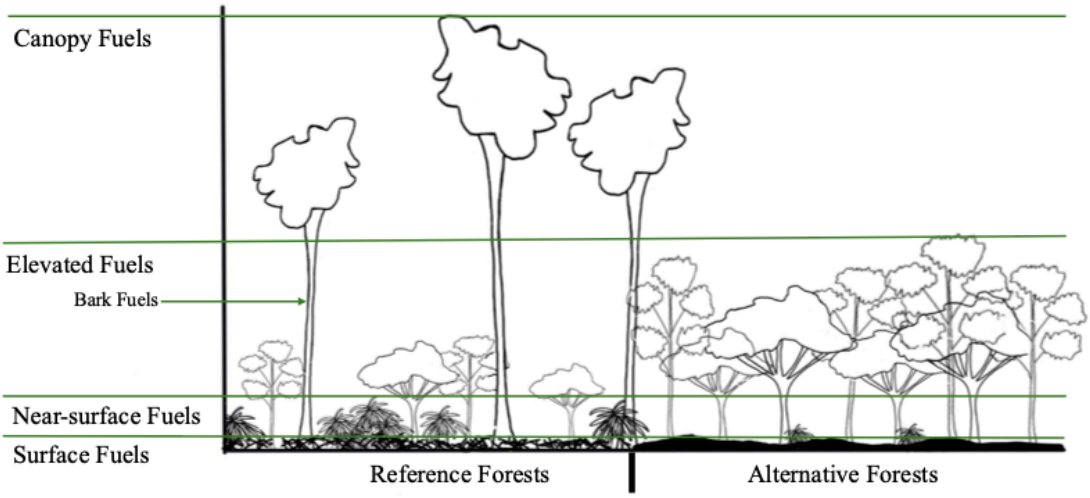


Figure 2

Conceptual diagram of the difference in fuel structure of reference and alternative states based on physical measures of forest structure outlined in Heap et al. (2026).

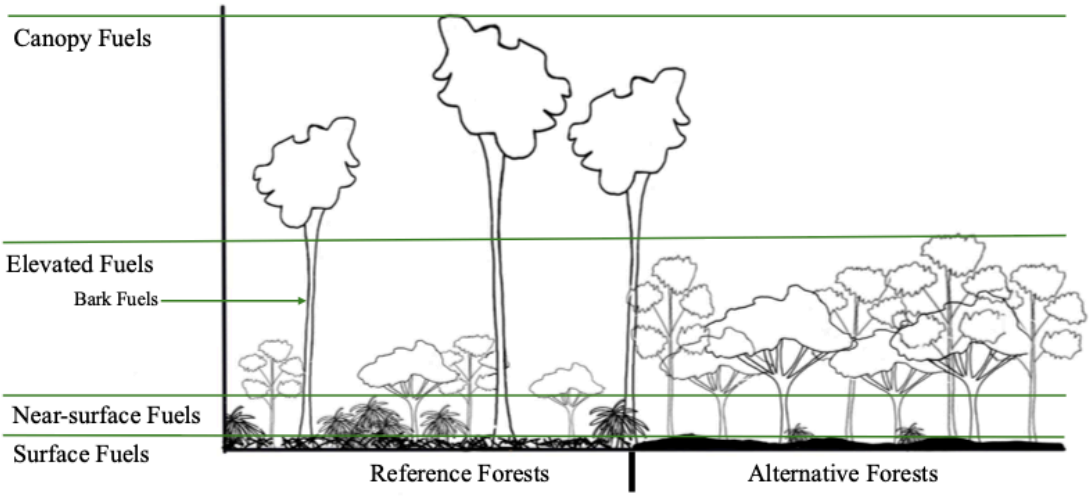


Figure 2

Conceptual diagram of the difference in fuel structure of reference and alternative states based on physical measures of forest structure outlined in Heap et al. (2026).

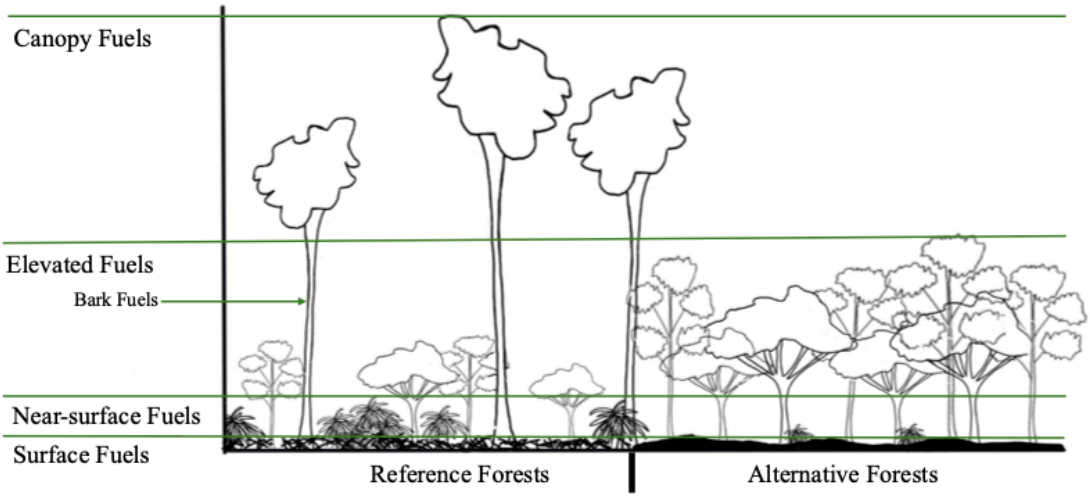


Figure 2

Conceptual diagram of the difference in fuel structure of reference and alternative states based on physical measures of forest structure outlined in Heap et al. (2026).

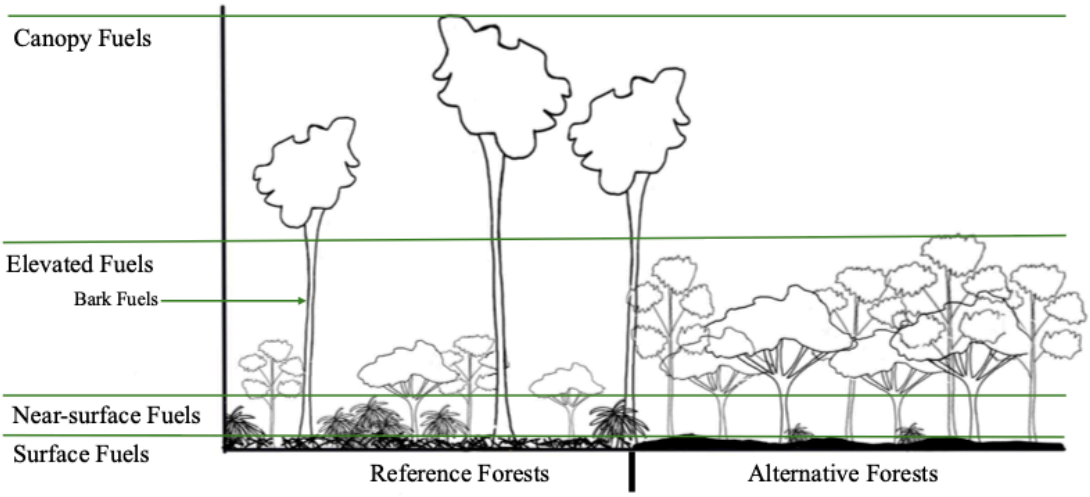


Figure 2

Conceptual diagram of the difference in fuel structure of reference and alternative states based on physical measures of forest structure outlined in Heap et al. (2026).



Figure 3

Representative examples of surface fuels from reference (a.) and alternative states (b.) once they have been replicated and sub-sampled into the fire containment rings. Figure 3c shows the ignition of the surface fuels within the flame propagation apparatus.



Figure 3

Representative examples of surface fuels from reference (a.) and alternative states (b.) once they have been replicated and sub-sampled into the fire containment rings. Figure 3c shows the ignition of the surface fuels within the flame propagation apparatus.



Figure 3

Representative examples of surface fuels from reference (a.) and alternative states (b.) once they have been replicated and sub-sampled into the fire containment rings. Figure 3c shows the ignition of the surface fuels within the flame propagation apparatus.



Figure 3

Representative examples of surface fuels from reference (a.) and alternative states (b.) once they have been replicated and sub-sampled into the fire containment rings. Figure 3c shows the ignition of the surface fuels within the flame propagation apparatus.

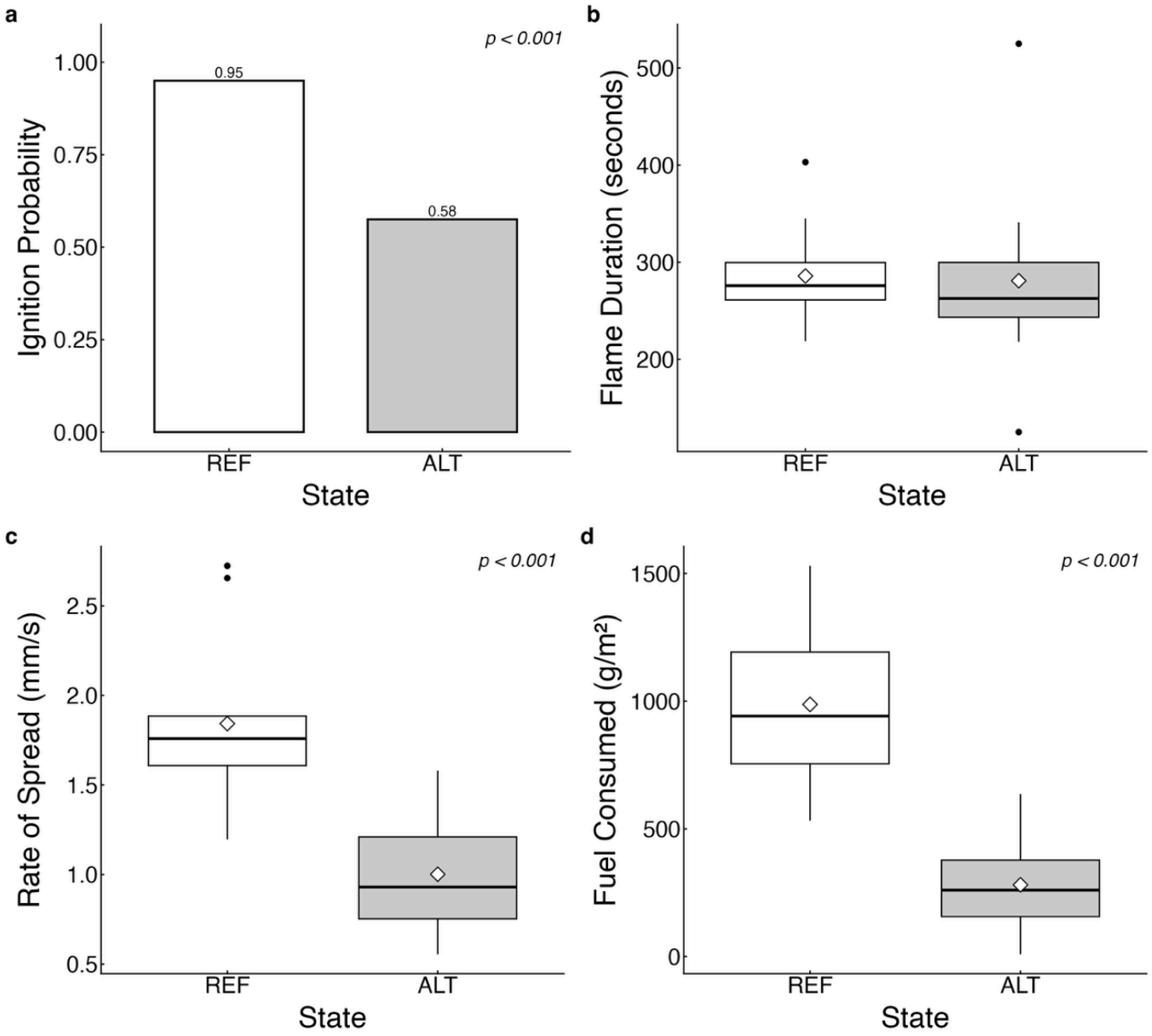


Figure 4

Comparisons of surface fuel flammability metrics between reference (REF) and alternative (ALT) forest states, including (a) ignition probability (ignitability), (b) flame duration (sustainability), (c) rate of spread (combustibility), and (d) fuel consumed (consumability). Boxplots show the distribution of values, with medians indicated by horizontal lines and means by diamonds. Ignition probability (a) is presented as the proportion of successful ignitions. Statistical significance between states was assessed using appropriate models for each response variable, with p-values shown within panels. Ignition probability, rate of spread, and fuel consumption were significantly lower in alternative states ($p < 0.001$), whereas flame duration did not differ between states. Results of post-hoc comparisons were summarised using compact letter displays, where groups sharing the same letter were not significantly different ($p > 0.05$). State-level means were calculated from site-level averages; therefore, reported standard errors reflect variability among sites rather than sampling error.

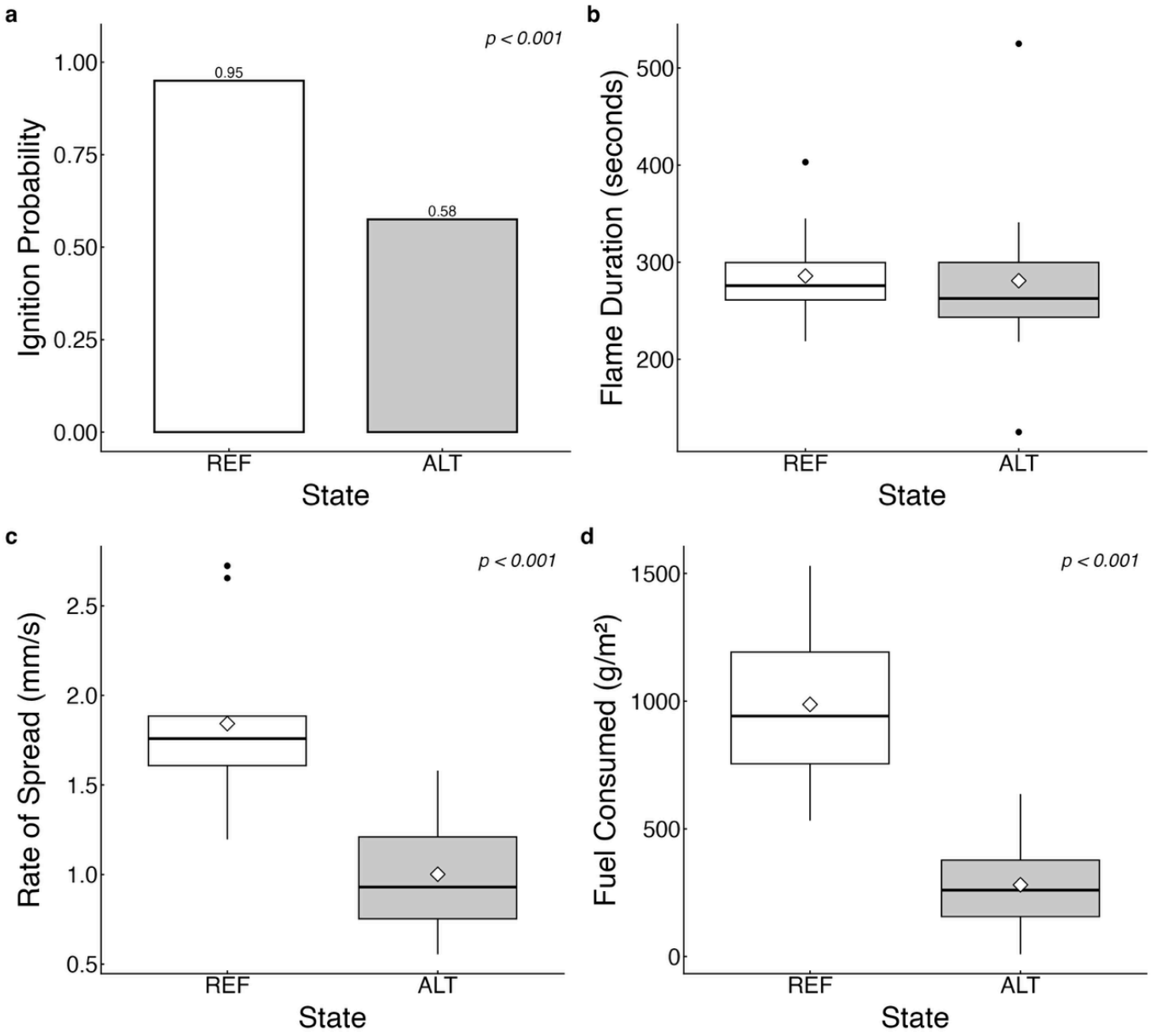


Figure 4

Comparisons of surface fuel flammability metrics between reference (REF) and alternative (ALT) forest states, including (a) ignition probability (ignitability), (b) flame duration (sustainability), (c) rate of spread (combustibility), and (d) fuel consumed (consumability). Boxplots show the distribution of values, with medians indicated by horizontal lines and means by diamonds. Ignition probability (a) is presented as the proportion of successful ignitions. Statistical significance between states was assessed using appropriate models for each response variable, with p-values shown within panels. Ignition probability, rate of spread, and fuel consumption were significantly lower in alternative states ($p < 0.001$), whereas flame duration did not differ between states. Results of post-hoc comparisons were summarised using compact letter displays, where groups sharing the same letter were not significantly different ($p > 0.05$). State-level means were calculated from site-level averages; therefore, reported standard errors reflect variability among sites rather than sampling error.

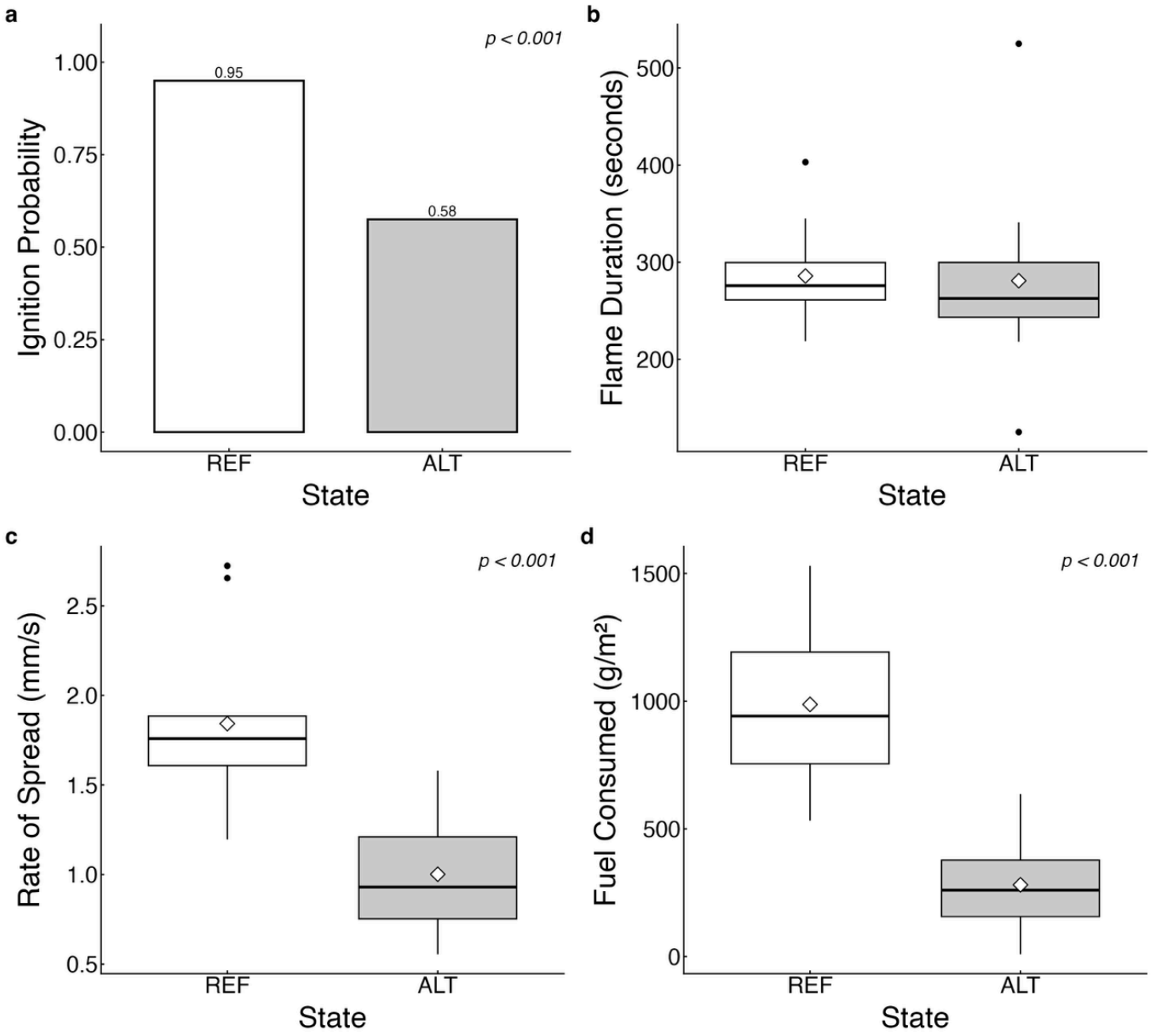


Figure 4

Comparisons of surface fuel flammability metrics between reference (REF) and alternative (ALT) forest states, including (a) ignition probability (ignitability), (b) flame duration (sustainability), (c) rate of spread (combustibility), and (d) fuel consumed (consumability). Boxplots show the distribution of values, with medians indicated by horizontal lines and means by diamonds. Ignition probability (a) is presented as the proportion of successful ignitions. Statistical significance between states was assessed using appropriate models for each response variable, with p-values shown within panels. Ignition probability, rate of spread, and fuel consumption were significantly lower in alternative states ($p < 0.001$), whereas flame duration did not differ between states. Results of post-hoc comparisons were summarised using compact letter displays, where groups sharing the same letter were not significantly different ($p > 0.05$). State-level means were calculated from site-level averages; therefore, reported standard errors reflect variability among sites rather than sampling error.

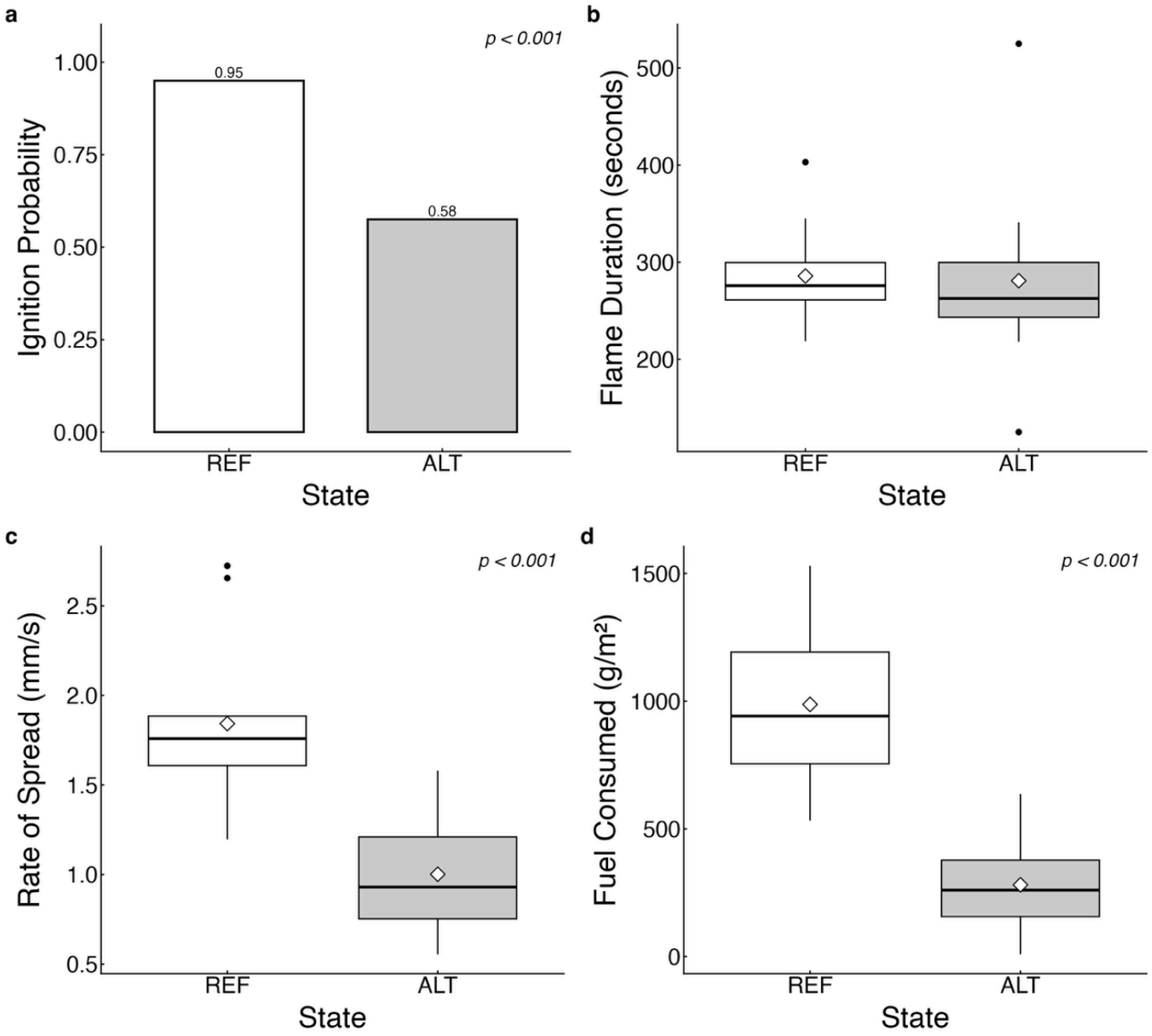


Figure 4

Comparisons of surface fuel flammability metrics between reference (REF) and alternative (ALT) forest states, including (a) ignition probability (ignitability), (b) flame duration (sustainability), (c) rate of spread (combustibility), and (d) fuel consumed (consumability). Boxplots show the distribution of values, with medians indicated by horizontal lines and means by diamonds. Ignition probability (a) is presented as the proportion of successful ignitions. Statistical significance between states was assessed using appropriate models for each response variable, with p-values shown within panels. Ignition probability, rate of spread, and fuel consumption were significantly lower in alternative states ($p < 0.001$), whereas flame duration did not differ between states. Results of post-hoc comparisons were summarised using compact letter displays, where groups sharing the same letter were not significantly different ($p > 0.05$). State-level means were calculated from site-level averages; therefore, reported standard errors reflect variability among sites rather than sampling error.

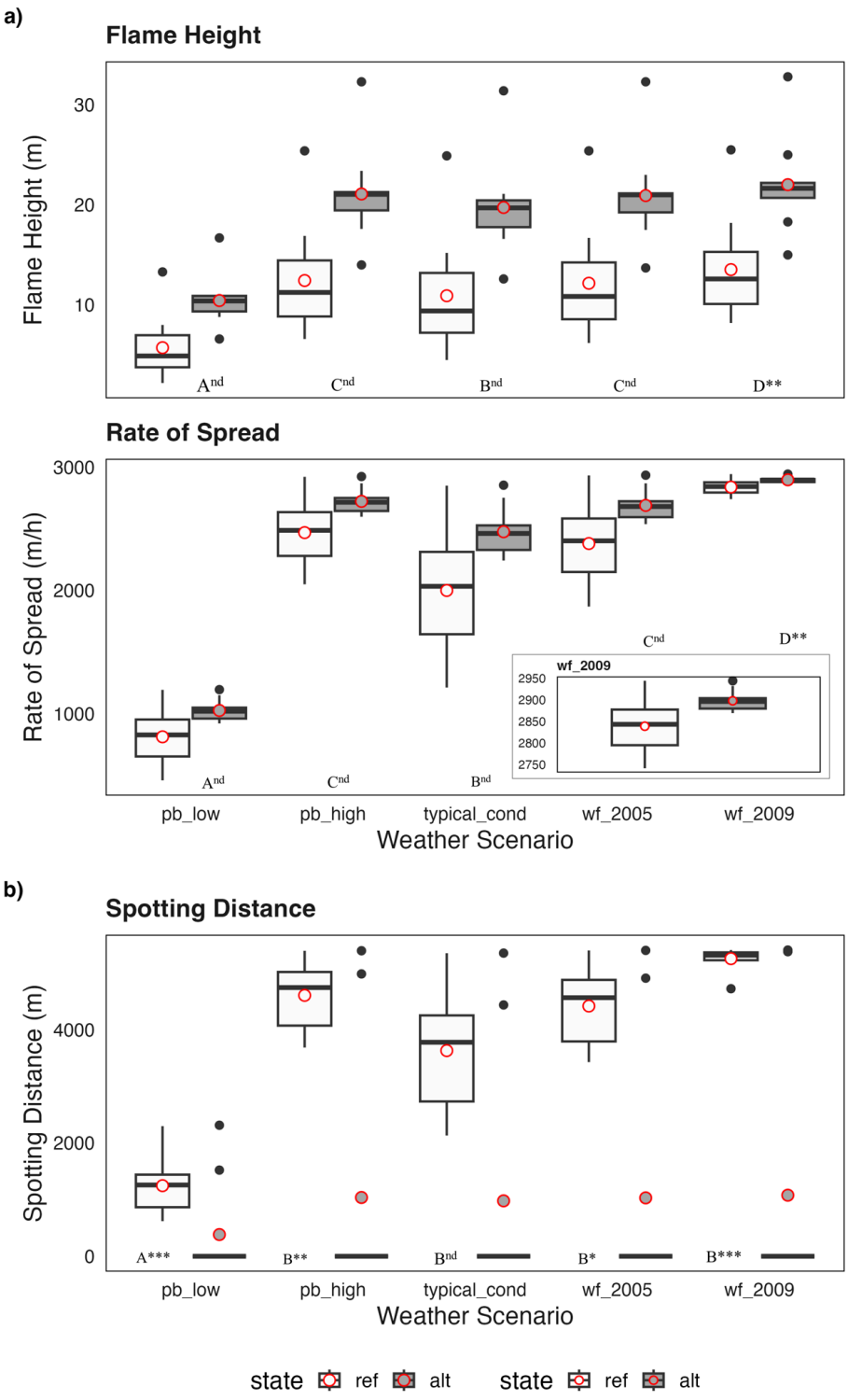


Figure 5

Modelled fire behaviour across five weather scenarios (pb_low, pb_high, typical_cond, wf_2005, wf_2009) in reference (ref) and alternative (alt) states: (a) flame height, (b) rate of spread, and (c) maximum spotting distance. Boxes show the median and interquartile range; red circles denote raw means. Uppercase letters indicate differences between weather scenarios (Sidak-adjusted compact letter display; scenarios not sharing a letter differ significantly at α = 0.05); for spotting distance, letters are shown for the reference state only, as spotting in the alternative state showed no significant variation among scenarios. Asterisks indicate the difference between states within a scenario (Tukey-adjusted pairwise contrasts: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; nd = no significant difference). For flame height, the state × scenario interaction was non-significant and flame heights were consistently higher in the alternative state across all scenarios ($p < 0.001$); per-scenario state contrasts are therefore not shown. All comparisons derive from aligned rank transform (ART) ANOVA.

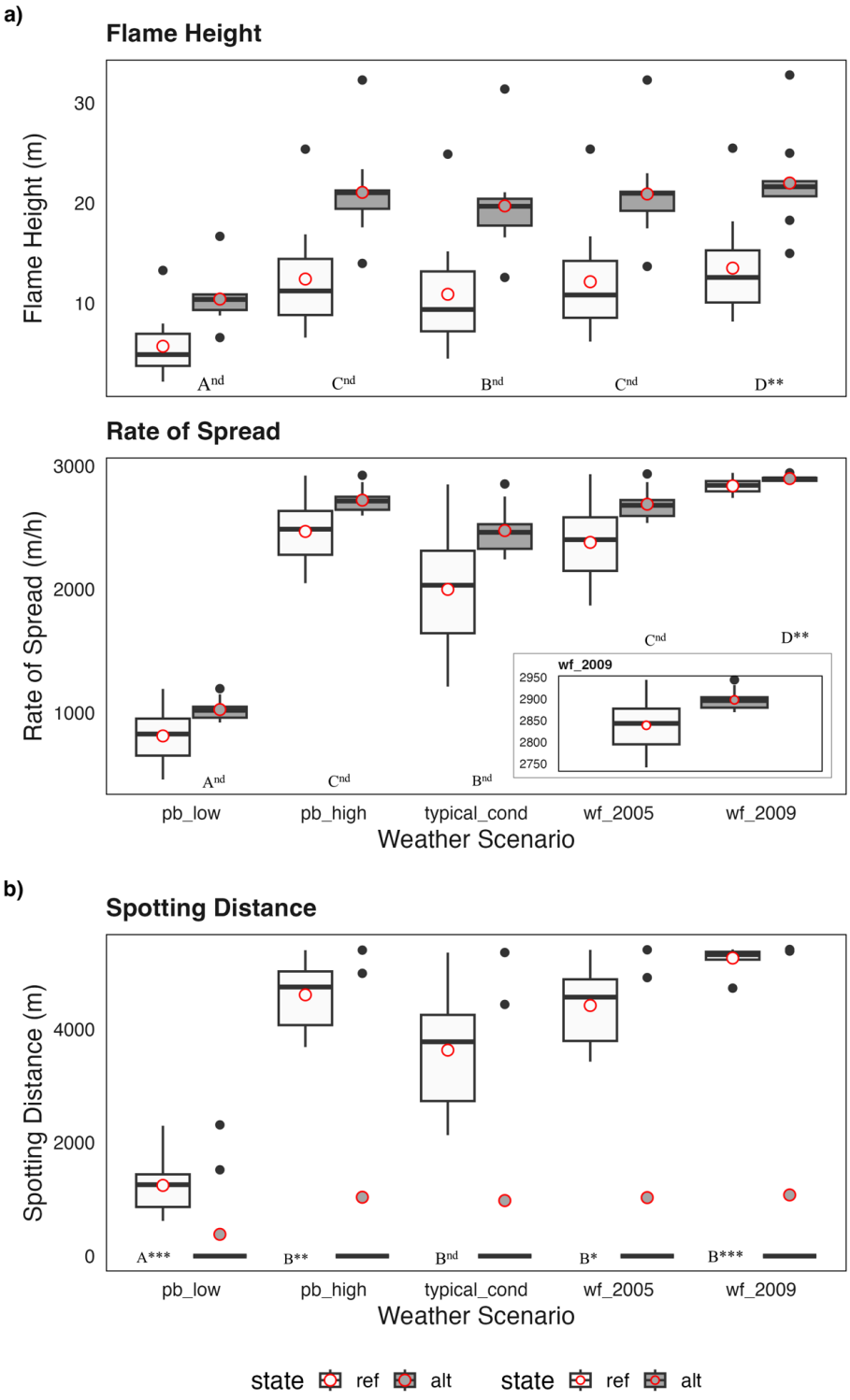


Figure 5

Modelled fire behaviour across five weather scenarios (pb_low, pb_high, typical_cond, wf_2005, wf_2009) in reference (ref) and alternative (alt) states: (a) flame height, (b) rate of spread, and (c) maximum spotting distance. Boxes show the median and interquartile range; red circles denote raw means. Uppercase letters indicate differences between weather scenarios (Sidak-adjusted compact letter display; scenarios not sharing a letter differ significantly at α = 0.05); for spotting distance, letters are shown for the reference state only, as spotting in the alternative state showed no significant variation among scenarios. Asterisks indicate the difference between states within a scenario (Tukey-adjusted pairwise contrasts: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; nd = no significant difference). For flame height, the state × scenario interaction was non-significant and flame heights were consistently higher in the alternative state across all scenarios ($p < 0.001$); per-scenario state contrasts are therefore not shown. All comparisons derive from aligned rank transform (ART) ANOVA.

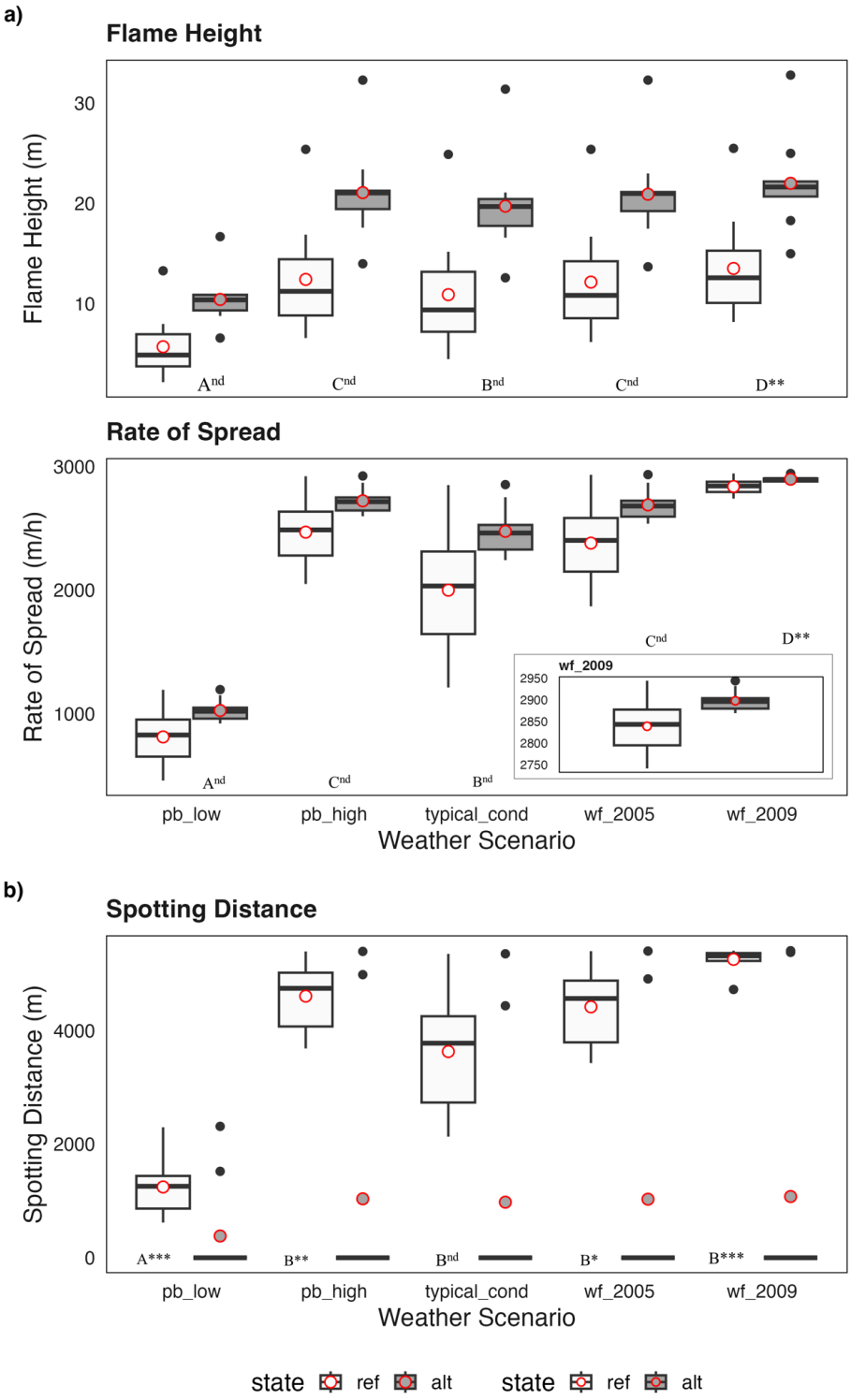


Figure 5

Modelled fire behaviour across five weather scenarios (pb_low, pb_high, typical_cond, wf_2005, wf_2009) in reference (ref) and alternative (alt) states: (a) flame height, (b) rate of spread, and (c) maximum spotting distance. Boxes show the median and interquartile range; red circles denote raw means. Uppercase letters indicate differences between weather scenarios (Sidak-adjusted compact letter display; scenarios not sharing a letter differ significantly at α = 0.05); for spotting distance, letters are shown for the reference state only, as spotting in the alternative state showed no significant variation among scenarios. Asterisks indicate the difference between states within a scenario (Tukey-adjusted pairwise contrasts: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; nd = no significant difference). For flame height, the state × scenario interaction was non-significant and flame heights were consistently higher in the alternative state across all scenarios ($p < 0.001$); per-scenario state contrasts are therefore not shown. All comparisons derive from aligned rank transform (ART) ANOVA.

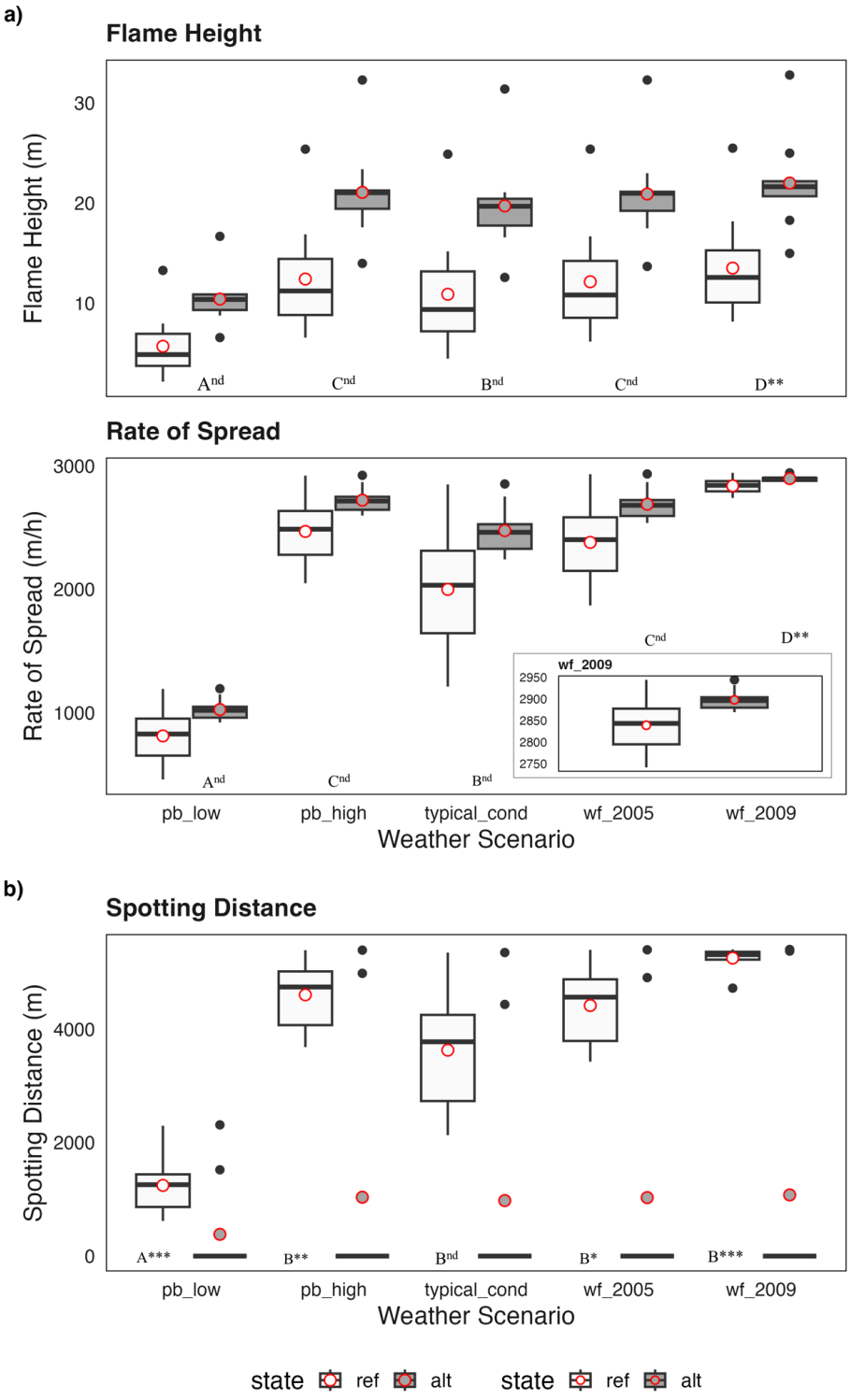


Figure 5

Modelled fire behaviour across five weather scenarios (pb_low, pb_high, typical_cond, wf_2005, wf_2009) in reference (ref) and alternative (alt) states: (a) flame height, (b) rate of spread, and (c) maximum spotting distance. Boxes show the median and interquartile range; red circles denote raw means. Uppercase letters indicate differences between weather scenarios (Sidak-adjusted compact letter display; scenarios not sharing a letter differ significantly at α = 0.05); for spotting distance, letters are shown for the reference state only, as spotting in the alternative state showed no significant variation among scenarios. Asterisks indicate the difference between states within a scenario (Tukey-adjusted pairwise contrasts: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; nd = no significant difference). For flame height, the state × scenario interaction was non-significant and flame heights were consistently higher in the alternative state across all scenarios ($p < 0.001$); per-scenario state contrasts are therefore not shown. All comparisons derive from aligned rank transform (ART) ANOVA.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial.docx
- SupplementaryMaterial.docx
- SupplementaryMaterial.docx
- SupplementaryMaterial.docx