






RESEARCH ARTICLE

The fuel–climate–fire conundrum: How will fire regimes change in temperate eucalypt forests under climate change?

Sarah C. McColl-Gausden¹  | Lauren T. Bennett¹  | Hamish G. Clarke^{2,3,4}  |
Dan A. Ababei^{1,5}  | Trent D. Penman¹ 

¹FLARE Wildfire Research, School of Ecosystem and Forest Sciences, The University of Melbourne, Parkville, Victoria, Australia

²Centre for Environmental Risk Management of Bushfires, Centre for Sustainable Ecosystem Solutions, University of Wollongong, Wollongong, New South Wales, Australia

³NSW Bushfire Risk Management Research Hub, Wollongong, New South Wales, Australia

⁴Hawkesbury Institute for the Environment, Western Sydney University, Penrith, New South Wales, Australia

⁵LightTwist Software, Melbourne, Victoria, Australia

Correspondence

Sarah C. McColl-Gausden, FLARE Wildfire Research, School of Ecosystem and Forest Sciences, The University of Melbourne, Parkville, VIC, Australia.
Email: mccoll.s@unimelb.edu.au

Funding information

Australian Government Research Training Program (RTP) Scholarship; Integrated Forest Ecosystem Research agreement between the Victorian Dept of Environment, Land, Water and Planning; ACT Government Environment and Sustainable Development Directorate; University of New South Wales Climate Change Research Centre; NSW Government Office of Environment and Heritage; The University of Melbourne

Abstract

Fire regimes are changing across the globe in response to complex interactions between climate, fuel, and fire across space and time. Despite these complex interactions, research into predicting fire regime change is often unidimensional, typically focusing on direct relationships between fire activity and climate, increasing the chances of erroneous fire predictions that have ignored feedbacks with, for example, fuel loads and availability. Here, we quantify the direct and indirect role of climate on fire regime change in eucalypt dominated landscapes using a novel simulation approach that uses a landscape fire modelling framework to simulate fire regimes over decades to centuries. We estimated the relative roles of climate-mediated changes as both direct effects on fire weather and indirect effects on fuel load and structure in a full factorial simulation experiment (present and future weather, present and future fuel) that included six climate ensemble members. We applied this simulation framework to predict changes in fire regimes across six temperate forested landscapes in south-eastern Australia that encompass a broad continuum from climate-limited to fuel-limited. Climate-mediated change in weather and fuel was predicted to intensify fire regimes in all six landscapes by increasing wildfire extent and intensity and decreasing fire interval, potentially led by an earlier start to the fire season. Future weather was the dominant factor influencing changes in all the tested fire regime attributes: area burnt, area burnt at high intensity, fire interval, high-intensity fire interval, and season midpoint. However, effects of future fuel acted synergistically or antagonistically with future weather depending on the landscape and the fire regime attribute. Our results suggest that fire regimes are likely to shift across temperate ecosystems in south-eastern Australia in coming decades, particularly in climate-limited systems where there is the potential for a greater availability of fuels to burn through increased aridity.

KEYWORDS

climate change, eucalypt, fire regime, forest, fuel feedbacks, wildfire

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs](https://creativecommons.org/licenses/by-nc-nd/4.0/) License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2022 The Authors. *Global Change Biology* published by John Wiley & Sons Ltd.

1 | INTRODUCTION

Fire regimes are changing across the globe. The number and extent of wildfires are increasing, as is the occurrence of extreme fire behaviors (Duane et al., 2021). The 2019/2020 fire season saw some of the largest fires on record in south-eastern Australia (Boer et al., 2020; Filkov et al., 2020) and the western United States (Higuera & Abatzoglou, 2021). Importantly, these changes have not been restricted to a single season. Recent changes to fire regimes have been linked to climatic factors such as warmer and earlier springs (Westerling et al., 2006), warm dry summers (Morgan et al., 2008), and increases in temperature and vapor pressure deficit (Abatzoglou & Williams, 2016). Changes to the fire regime include increasing wildfire activity in the western United States (Westerling, 2016) with associated increases in the extent of high-severity fire (Parks & Abatzoglou, 2020). There is evidence in Canada that large fires (>200 ha) are getting larger, and fire seasons are getting longer (Hanes et al., 2019). Studies in both France and Australia show increases in the severity of fire weather (hot, dry conditions) over the last 50 years (Barbero et al., 2020; Clarke et al., 2013), which has increased the likelihood of summers with extreme fire danger in France (Barbero et al., 2020) and has been associated with increases in area burned in forest bioregions of Australia (Bradstock et al., 2014; Fairman et al., 2016). While fire is a natural phenomenon in many of these parts of the world, changing fire regimes attributable to human-caused climate change (Barbero et al., 2020) or other anthropogenic factors (Cattau et al., 2020; Haggmann et al., 2021) will increase fire-related risks to life and property through increased exposure of assets (Moritz et al., 2014), and to biodiversity through inappropriate fire regimes for some species (Harvey et al., 2016).

Four key conditions (otherwise known as fire 'switches') must be met for fires to occur; there must be biomass (fuel), the fuel must be available to burn (be sufficiently dry), the weather needs to meet conditions for fire spread, and an ignition must occur (Bradstock, 2010; Pausas & Keeley, 2021). Climatic change can influence fire regimes through at least three of the four switches both directly, by affecting fire weather and fuel moisture, and indirectly, by affecting fuel load and structure. Severe fire weather is associated with high temperatures, low humidity, and high wind speed. The current predictions of future fire weather tend to show an increase in the magnitude of fire weather in fire-prone regions throughout the world; however, the degree of change varies between biomes (Clarke et al., 2013; Pausas, 2004; Pitman et al., 2007; Suppiah et al., 2007). Changes to fire weather also influence fuel moisture and hence the availability of fuel to burn. Fuel can only ignite if it is dry enough to burn, therefore, a drying climate will alter the broad-scale patterns of fuel moisture and connectivity, changing the propensity for large fires to occur across landscapes (Caccamo et al., 2012; Ellis et al., 2021; Nolan et al., 2016). Megafires (>10,000 ha in extent [Stephens et al., 2014]) in recent years have been strongly linked to drought that increase fuel dryness and prime landscapes to burn (Abram et al., 2021; Higuera & Abatzoglou, 2021; Nolan, Boer, et al., 2020). However, fire, climate, and fuel processes are continually interacting and other

important controls of fire regimes, such as biotic feedbacks—that could influence fuel accumulation and structure—are often neglected in research that explores future fire regimes.

Climate change has the potential to influence both the composition and structure of vegetation communities (Albrich et al., 2020; Harvey et al., 2016). Live and dead vegetation are the fuel in wildfires; hence, any changes to vegetation may alter fire occurrence and behavior (Bradstock, 2010). Long-term climate and short-term weather can interact to influence vegetation persistence, where, for example, mature trees survive in a warming, drying climate but fail to regenerate in the prevailing climate (Jackson et al., 2009; Parks et al., 2016). These interactions can lead to trailing-edge disequilibrium, where the directional effects of climate do not immediately result in changes to vegetation that is dominated by long-lived species, which can survive and persist despite not being capable of regenerating in a newly unsuitable climate (Sheth & Angert, 2018). On a shorter timescale, a fire that kills mature individuals, combined with inappropriate climate or weather for regeneration could increase the rate of vegetation changes and potentially result in the loss of some species. For example, desiccation in the post-fire environment markedly increased seedling mortality of multiple serotinous shrubs in many Cape fynbos communities of South Africa (Mustart et al., 2012). Multidecadal shifts in vapor pressure deficit, soil moisture, and maximum surface temperature have also resulted in fewer opportunities for postfire regeneration of low-elevation conifers in the western United States (Davis et al., 2019). Similar instances of multi-species regeneration failure could contribute to species losses and ecosystem conversions that could alter both fuel load (the amount of fuel in an ecosystem) and structure (how the fuel is arranged vertically and horizontally) and therefore subsequent fire behavior.

Climate mediated changes to fire regimes will vary depending on the vegetation community (Abatzoglou & Williams, 2016). The type and degree of change could differ depending on what constrains fire in that community. Ecosystems can be fuel-limited—having insufficient fuel biomass to burn most years, such as in xeric shrublands or grasslands—or climate-limited—where cool, moist climatic conditions mean that fuels are not available to burn in most years, such as in tropical or some temperate ecosystems (Bradstock, 2010; Krawchuk & Moritz, 2011). However, this is not a binary classification with many ecosystems falling along a climate-limited fuel-limited continuum (McKenzie & Littell, 2017). For example, tropical savannas occur in regions with an annual wet season, allowing biomass growth and fuel accumulation. This is followed by the annual dry season, which often reduces fuel moistures to levels conducive to fire spread (Bradstock, 2010). Fire occurrence in tropical savannas is therefore not clearly limited by either fuel amount or fuel availability. Systems might also move along the continuum as climate, fire, and vegetation interact. Positive feedbacks between increased fire occurrence linked to warmer and drier conditions have sometimes led to, or are predicted to lead to, community-type conversions with fire intolerant species replaced by fire tolerant species that are typically more flammable (Landesmann et al., 2021).

The key attributes of the fire regime are often defined as fire intensity, frequency, season of occurrence, size, and heterogeneity (Bond & Keeley, 2005; Gill, 1975; Gill & Allan, 2008) with the combination of attributes producing the variation across different ecosystems. Forest ecosystems of temperate Australia vary along the fuel-limited and climate-limited continuum with higher-biomass forests often sitting closer to the climate-limited end, and open woodlands positioned towards the fuel-limited end. Higher-biomass forests include the relatively restricted distributions of temperate rainforests, which are rarely burned (>100 years) due to high fuel moisture (Murphy et al., 2013). Eucalypt-dominated closed and open forests also sit closer towards the climate-limited end and are typically burned every 20–100 years by high-intensity fires, often driven by high fuel loads and preceding drought (Cawson et al., 2018; Murphy et al., 2013). In comparison, eucalypt-dominated woodlands and mallee are typically characterized by lower comparative fuel loads and are burned by low- to mid-intensity litter or grass fires every 20–100 years (Montreal Process Implementation Group for Australia & National Forest Inventory Steering Committee, 2018; Murphy et al., 2013). Climate change could therefore influence fire regimes within forest ecosystems of temperate Australia in a variety of ways. In some areas, we are already seeing fire weather influencing the likelihood of extreme forest fires (Abram et al., 2021). However, the magnitude of change may not be spatially uniform, with smaller increases predicted for the summer rainfall and more climate-limited ecosystems, and greater increases for the winter rainfall and fuel-limited ecosystems (Clarke et al., 2011). The contrasting fire regimes and fuel-climate conditions in native vegetation will interact under changing climate to influence the nature of future fire regimes, an interaction that remains largely underexamined.

Understanding of potential shifts in fire regimes and underlying mechanisms is needed to manage and conserve fire-prone ecosystems under changing climates. To better assess the potential for change, both short- and long-term processes, such as short-term weather versus long-term climate, need to be captured along with variation and uncertainty across landscapes. Deterministic models often cannot capture this uncertainty, so approaches are required that identify and account for sources of uncertainty. Forecasting fire regimes is a challenging task due to the interacting nature of climate, fuels, and fire, but one well suited to process-based simulation models due to their potential to explicitly capture complex interactions as they vary in both space and time. Simulation models—predictive models used for the purposes of exploration, scenario-building, projection, prediction, and forecasting (Loehman et al., 2020; Perera et al., 2015)—are widely used to interpret fire behavior and predict changes in vegetation and other ecosystem attributes (Andrews et al., 2008; Finney, 1998; Tymstra et al., 2007). Fire models range in complexity and scale from small-scale and detailed fluid-dynamics models (Mcgrattan et al., 2013) to global models of fire occurrence (Bond & Keeley, 2005). Landscape-scale models capture fire, climate, and vegetation interactions at intermediate temporal (days to years to decades) and spatial (10^0 – 10^3 km²) scales relevant to environmental processes and most management decisions, and therefore, have

the potential to increase our understanding of fire regimes (Keane et al., 2015).

In this study, we use a landscape fire modelling framework to simulate fire regimes over decades to centuries in six forested landscapes across temperate Australia. Our approach uses fire behavior simulations combined with models of future fuel and climate projections to predict fire regimes and associated uncertainties under different scenarios to explore the independent and interacting effects of predicted future fuels and future fire weather. Based on previous research in forest landscapes (Abatzoglou et al., 2021; Canadell et al., 2021; Duane et al., 2021), we anticipate future fires will become more extensive and of higher intensity, the fire interval will reduce, and fire seasons will become longer, but that these changes will vary according to if the ecosystem is more climate-limited or more fuel-limited. We also anticipate that the direct influence of climate change on fire weather will be the most important factor influencing future fire regimes in temperate Australia, especially in landscapes dominated by more climate-limited ecosystems, but that the indirect effect of climatic change on fuel load and structure may offset some of the fire regime shifts in all landscapes.

2 | MATERIALS AND METHODS

2.1 | Study area selection

The six study areas span the temperate region of south-eastern Australia from the Adelaide Hills in the west to the Blue Mountains in the north-east (Figure 1). Study areas vary between 5300 km² to 14,000 km² to accommodate different arrangements of native vegetation and historic fire patterns (Figure 1). Mean annual temperatures and potential evapotranspiration (PET) are greatest in the northern most areas (Adelaide Hills, Blue Mountains) and least in the most elevated areas along the Great Dividing Range (Alpine and ACT; Figure 1). The dominant rainfall season varies from east to west with the most north-eastern study area dominated by summer or uniform rainfall (Blue Mountains) and the most westerly dominated by winter rainfall (Adelaide Hills). All of the study areas have more than 10% native vegetation with a dominant eucalypt overstorey (Table S2). The vegetation generally varies from open forests and woodlands in the most north (Blue Mountains) and westerly sites (Adelaide Hills, Grampians) to tall eucalypt forests in the cooler and wetter areas (Alpine, East Gippsland; Table S2). The six study areas span a climate-limited fuel-limited continuum using net primary productivity (Haverd et al., 2013) as an indication of potential fuel load, and the fraction of time monthly PET exceeds precipitation (Boer et al., 2016) as a representation of climate (Figure 2).

2.2 | Simulation modelling design

We modelled the effects of climate change on fuel hazard and weather on the fire regime in each of the study areas. We consider

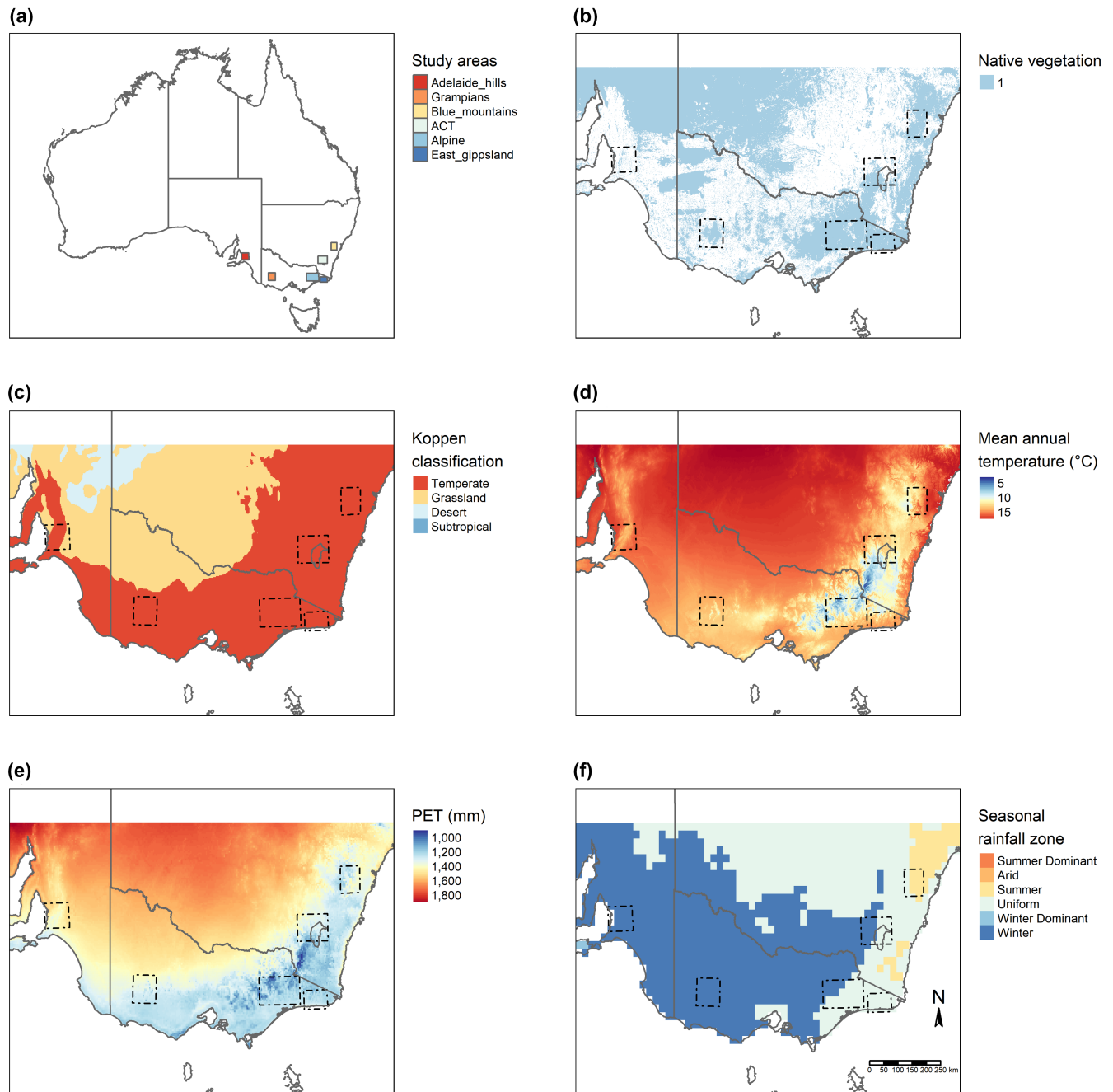
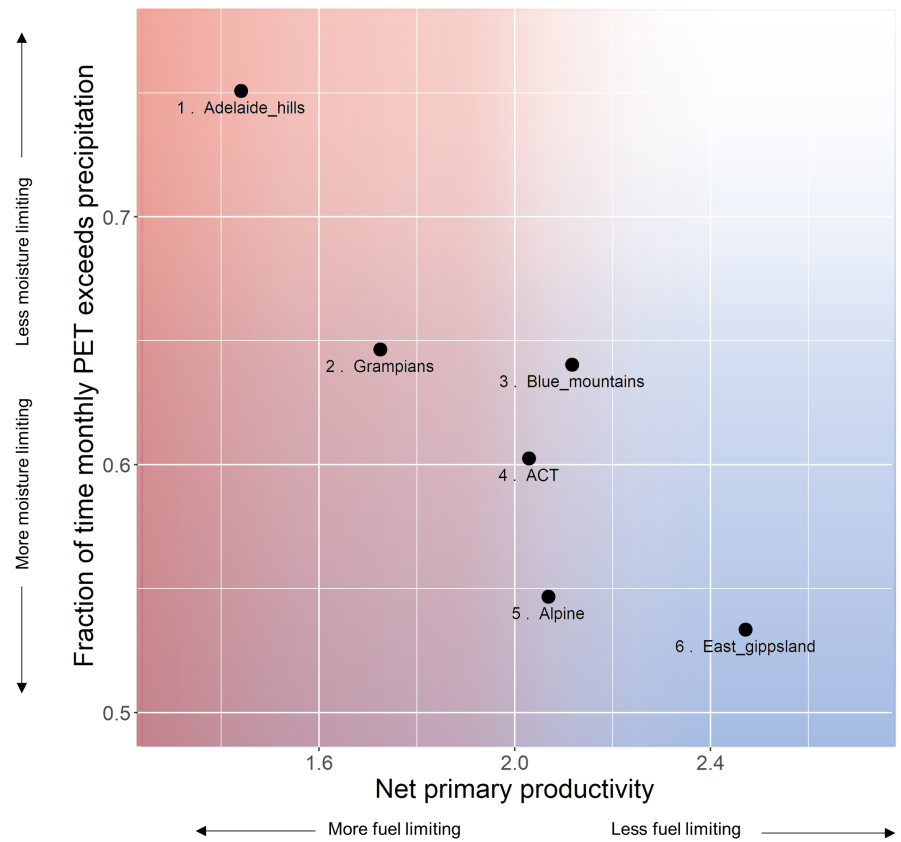


FIGURE 1 (a) Study areas- order represents most fuel-limited to most climate limited: Adelaide hills (dark orange), Grampians (orange), Blue Mountains (yellow), Australian Capital Territory (light blue), alpine (blue), East Gippsland (dark blue). (b) Native vegetation (light blue). (c) Koppen classification: Temperate (dark orange), grassland (light orange), and desert (light blue). (d) Mean annual temperature (dark blue to dark orange). (e) PET (dark blue to dark orange). (f) Seasonal rainfall zone: Summer dominant (dark orange), arid (light orange), summer (yellow), uniform (pale blue), winter dominant (blue), and winter (dark blue). PET, potential evapotranspiration.

the impact of climate change in two separate pathways that are tested independently and interactively. Fuel hazard is influenced by changes to annualized values of climate such as mean annual temperature (see below), whereas weather is influenced through the predicted hourly values of variables such as temperature, humidity, and wind. We acknowledge that while the base data for these values are not truly independent, we wish to focus on the independent responses (i.e. fuel vs. weather). To examine fuel and weather effects

independently, our weather and fuel scenarios consist of present weather and present fuel (Pw_Pf), present weather and future fuel (Pw_Ff), future weather and present fuel (Fw_Pf), and future weather and future fuel (Fw_Ff; Figure 3). The weather and fuel scenarios were run with each of six climate models (see Section 2.7) giving 24 simulation scenarios for each study area. The landscape fire modelling framework 'FROST' (see below) was run for 120 years in each simulation scenario to simulate effects of the combined weather and

FIGURE 2 Location of the six study areas along a gradient of potential fuel load (x axis) represented by net primary productivity (Haverd et al., 2013), and climate (y axis) represented by the fraction of time monthly PET exceeds precipitation (Boer et al., 2016). The red gradient represents those areas and ecosystems where fire regimes are more likely to be fuel limited (e.g. shrublands or grasslands), whereas the blue gradient represents those areas and ecosystems where fire regimes are more likely to be climate limited (e.g. tall forests). PET, potential evapotranspiration.



fuel conditions on the fire regime. Each simulation scenario was replicated 50 times to represent uncertainty in the fire simulations as many conditions are probabilistic, such as the simulation start day within the weather data (i.e. changes with every replicate), and the ignition likelihood. The first 20 years of each simulation represent a 'burn in' period and were removed prior to analysis allowing the regime tool to build a fire history appropriate for the conditions in the simulation.

Outputs from FROST include local and landscape fire impacts. Local impacts record values for each cell (180m cell, 3.24 ha) in any simulated fire. These values include fire intensity, flame height, flame depth, ember density, convection, fire weather, and rate of spread. Landscape-level impacts include data relating to the start and end time of each individual fire and the burnt area within a given period.

2.3 | Fire regime simulator

We simulated fire regimes over 120 years using the landscape fire modelling framework 'FROST' (Fire Regime and Operations Simulation Tool). FROST uses a framework of "modules" to combine fire behavior simulation with Bayesian network (BN) models to capture and account for uncertainty in the modelled systems (Penman et al., 2015). The central framework is made up of a weather module, ignition module, and fuel module, all of which inform a fire event simulator, PHOENIX RapidFire (Tolhurst et al., 2008) (Figure 3).

2.3.1 | Weather module

The weather module uses daily weather to determine the daily number of ignitions, and hourly weather to simulate fire behavior when ignitions occur. Weather data for this project were from the 'NARClIM' project (NSW and ACT Regional Climate modelling; see Section 2.4) (Evans et al., 2014).

2.3.2 | Ignition module

The ignition module calculates ignition probability using weather, proximity to roads, and house density as inputs to a BN (Clarke, Gibson, et al., 2019). The ignition module then predicts the number and time of ignitions for each day across the simulation area using a second BN based on historical ignitions. Across the 24 scenarios, the proximity to roads and housing density is static and does not account for changes over time.

2.3.3 | Fuel module

The fuel module predicts hazard ratings of fine fuels (<6 mm thick dead and <3 mm thick live plant material) in each of the four strata relevant to native ecosystems of temperate Australia (surface, near-surface, elevated, and bark) using separate models for native fuels, and non-native fuels (predominantly agricultural land in our study

SCENARIO SET UP

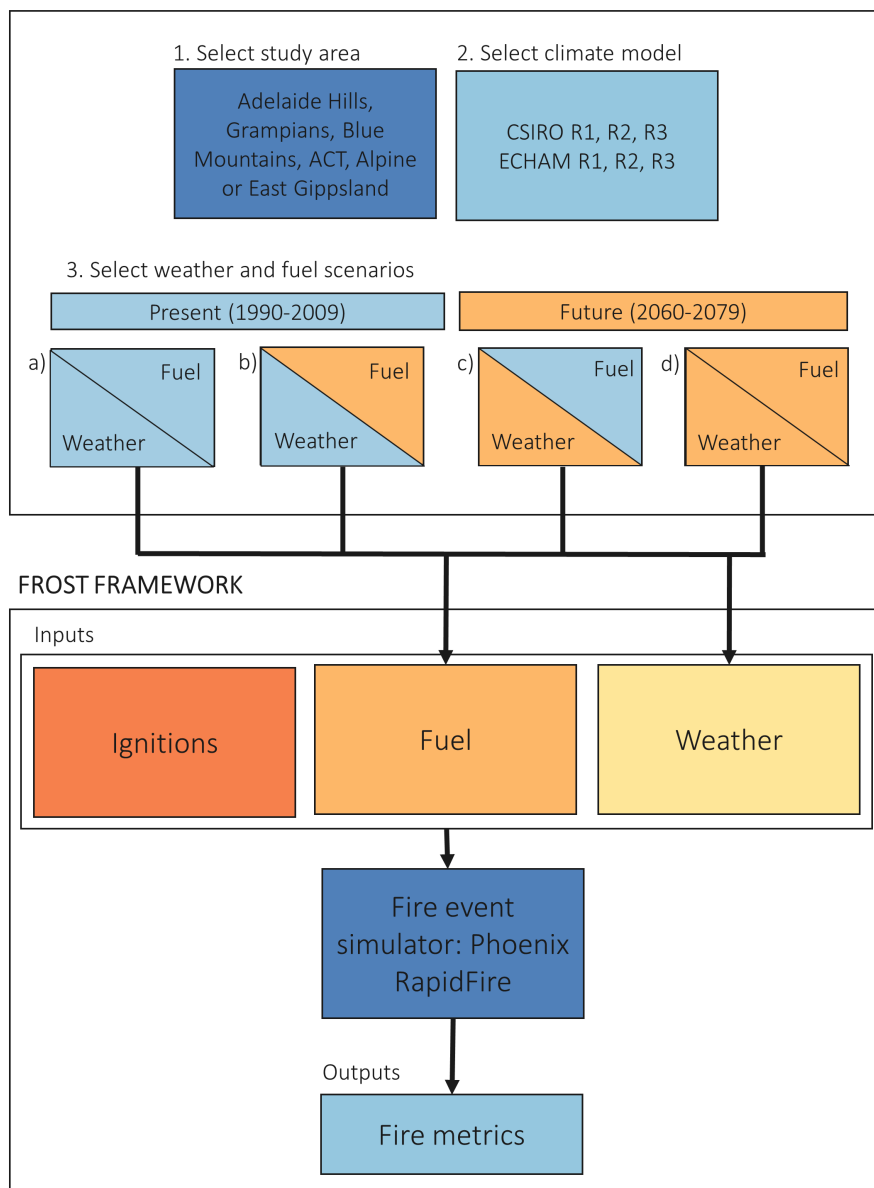


FIGURE 3 The study's overall simulation framework. A simulation run involved selecting the study area and one of six regional climate models, and then one of four weather/fuel scenarios. These data were used to drive FROST, the fire modelling framework, where the fire regime simulations were replicated 50 times and run over 120 years for a total of 24 scenarios per study area.

areas). Surface fuels are defined as leaves, twigs, bark and other fine fuel lying on the ground (Hines et al., 2010). Near-surface fuels are connected to the ground but not lying on it and less than 1 m in height, that is grasses (Hines et al., 2010). Elevated fuels are generally upright in orientation, are between 1 and 5 m tall and are physically separated from the surface fuels (Hines et al., 2010). Bark fuels are the bark attached to tree stems and branches at all heights from the ground to canopy (Hines et al., 2010). Fuel hazard ratings are measured in the field using visual assessments of the horizontal and vertical continuity of fine fuel in each fuel strata that would burn in the flaming front of a fire (McColl-Gausden et al., 2020). The fuel predictions focus on fine fuel as they contribute the most to rate of spread and flame height (Hines et al., 2010).

Predictions of native fuel hazard ratings by strata were made using the empirical models of McColl-Gausden et al. (2020), which are random forest models developed from tens of thousands of fuel

hazard assessments across south-eastern Australia. These models predict fuel hazard as a function of seven predictor variables: three climate, three soil, and time since fire in years (Table S1). These seven predictors allowed us to model variations in future fuel hazard directly from biophysical data without the need to model potential changes in the distribution or composition of vegetation classes. Climate variables used in predictions of present native fuel hazard were three bioclimatic variables from WorldClim (Busby, 1991): annual mean temperature (bio1), max temperature of the warmest month (bio 5), and precipitation of the warmest quarter (bio 18). The same three bioclimatic variables were used for the predictions of future native fuels except the values were derived from each of the future climate models (see Section 2.4). Soil variables were from the Soil and Landscape Grid of Australia (Viscarra Rossel et al., 2015), which vary spatially but were held constant over time, that is, between present and future simulation scenarios, based on a lack of

quantitative evidence of soil changes with fire and climate. Time since fire was dynamically calculated when fires occurred in a simulation to account for fire feedbacks on fuel within both present and future simulations. If no fires occurred within a simulation year in a simulation cell, time since fire was advanced by 1 year. Average native fuel hazard for each fuel strata over a time series of time since fire is presented in the Supplementary Data (Figures S1–S4). The exponential fuel model was used for non-native fuels where fuel hazard accumulation was modelled for each strata within each vegetation type using Olson curves (Olson, 1963) based on time since fire, where time since fire was also dynamically calculated on a per fire or yearly basis (Cirulis et al., 2020; Penman et al., 2013) (Table S1). All predicted hazard ratings of native and non-native fuels per strata were subsequently converted into fuel loads (as per equations in Table S1) to be used within the fire event simulator, PHOENIX RapidFire (Tolhurst et al., 2008).

On a single simulation day, the ignition module predicts the number and timing of likely ignitions based on the two BNs. If the ignitions are predicted to spread, the fire event simulator is initiated with hourly weather with all fires growing and spreading from individual ignition locations concurrently so fires can interact with each other. Fuel consumption is calculated at the end of each day and fuels are grown at the end of the fire season based on the fuel accumulation models in the fuel module. Fires are simulated at a resolution of 180 m as recommended by Chong et al. (2013). While finer resolution (e.g. 90 m) simulations may be able to capture fine detail at site-level studies, in our case the benefits do not outweigh the large increase in processing time that would be required for landscape-scale studies (Chong et al., 2013).

2.4 | Climate model selection

All weather and climate data used in this study come from the NARCLiM project (Evans et al., 2014). The NARCLiM project provides dynamically downscaled climate projections for south-east Australia at a 10-km resolution. The data include hourly surface air temperature, surface specific humidity, near-surface wind speed and direction, surface wind speed, and surface pressure, which are required for fire simulations and are referred to as weather in this study. The data also included standard annual bioclimatic variables [BIOCLIM (Busby, 1991)], which are referred to as climate in this study. NARCLiM uses the SRES A2 emissions scenario (IPCC, 2007), which projects a warming of the planet by approximately 3.4°C by 2100 and is comparable to the subsequent scenario RCP8.5 (Moss et al., 2010). The NARCLiM project includes four equally plausible global climate models (GCMs) selected for their skill, independence, and capacity to span a range of alternate climate scenarios (Evans et al., 2014). Global climate models have cell grids that can be hundreds of kilometers wide and are not useful for projecting regional differences. Thus, three regional climate models (RCMs) are used to downscale the four GCMs to a grid size of 10 km, which better represents features important for local and regional weather and fire behavior such

as topography and coastlines. The resulting 12-member NARCLiM ensemble has been extensively evaluated and used by managers and policymakers (Clarke, Tran, et al., 2019; Di Luca et al., 2016; Evans et al., 2017; Fita et al., 2017; Olson et al., 2016). For this study, we selected two of the four GCMs—ECHAM5 and CSIRO Mk3—and all three associated RCMs for each GCM, resulting in a 6-member climate ensemble. Selection of these six climate projections was based on their skill in simulating observed mean and extreme fire weather conditions in south-eastern Australia as represented by Forest Fire Danger Index (FFDI; Clarke & Evans, 2019). FFDI has strong correlations with the burned area and frequency of forest fires (Canadell et al., 2021). The selected ensemble members are on the drier end of the spectrum and have larger increases in fire danger compared to the omitted ones meaning our selection can be viewed as the worst-case scenarios, which allows the exploration of fire behavior limits in temperate Australia. However, none of the 12 NARCLiM ensemble members project substantial decreases in fire danger (Clarke & Evans, 2019). The climate projections contain two epochs of data: 1990–2009 (present) and 2060–2079 (future). Because the NARCLiM data contain 20 years of climate time series data for each epoch, these data were looped six times to cover the 120-year simulation period. Across the six study areas and six climate projections, precipitation is projected to change between present and future conditions by between +18% in the Blue Mountains to –18% in the Adelaide Hills. Mean temperature is projected to increase by between 1.2°C in the Grampians to 2.5°C in the Blue Mountains (Figure S5).

2.5 | Data analysis

2.5.1 | Fire regime attributes

We used five fire regime attributes in our analysis: (i) annual area burnt, (ii) annual area burnt at high intensity, (iii) fire interval, (iv) fire interval of high-intensity fires, and (v) season midpoint. The attributes relate only to native vegetation, that is all other cell types are masked out of the analysis, except for season midpoint which incorporates all cells. These represent key components of the fire regime—namely, fire frequency, intensity, seasonality, and extent (Gill, 1975; Gill & Allan, 2008; Pausas & Keeley, 2009)—and are important determinants of ecosystem processes in fire-adapted systems (Steel et al., 2021). Annual area burnt per scenario was calculated as the area burnt per year (each an average of 50 replicates) averaged over the 100-year simulation analysis period. Annual area burnt at high intensity was calculated in the same way but only included cells that were burnt at intensities greater than 10,000 kW/m. Fire interval was defined as the mean fire interval across the 100-year simulation analysis period (only cells burnt at an intensity greater than 10,000 kW/m for high-intensity inter-fire interval). The wildfire season in FROST is a fixed period between 15th November and the 15th March (i.e. the last month of spring to the first month of autumn based on historical fire seasons in temperate Australia); therefore, to calculate season midpoint, we used the number of days from the

start of the wildfire season to when 50% of the total area burnt in that season was reached.

2.5.2 | Statistical analysis

To assess the independent and interactive effects of weather and fuel on each of the fire regime attributes, we used linear mixed models (LMMs) in the lme4 package (Bates et al., 2015) in R version 3.4.0.2 (R Core Team, 2020). Climate model was included as a random effect in all LMMs. The fuel epoch (present or future) and the weather epoch (present or future) were considered as fixed effects. To assess LMM assumptions, we used residual diagnostic tests using the DHARMA package (Hartig, 2020). Annual area burnt and annual area burnt at high intensity were log transformed to meet LMM assumptions. We calculated marginal (R^2_m) and conditional (R^2_c) coefficients of determination to summarise the explanatory power of the models for each of the six study areas using the MuMIn package (Barton, 2009) in R. We explored the relationship between fuel and weather epoch and each fire regime attribute by considering size and uncertainty (95% confidence intervals) of standardized model coefficients.

3 | RESULTS

3.1 | Fire regime predictions

Fire regimes were predicted to shift under future weather and future fuel conditions. However, the different fuel and weather scenarios influenced these shifts. Compared with current predictions (Pw_Pf), future weather consistently increased annual area burnt and annual area burnt at high intensity both with and without future fuels (Fw_Ff and Fw_Pf respectively; Figure 4a,b). In addition, these weather effects were stronger in more climate-limited study areas (Figure 5a,b). Consistent with increased fire extent, the intervals between fires, including fires of high intensity, were decreased in all landscapes under future weather both with and without future fuels (Fw_Ff and Fw_Pf respectively; Figure 4c,d), although this effect was strongest in those study areas towards the middle of the fuel-climate continuum (Grampians, Blue Mountains and ACT; Figure 5c,d). Season midpoint was consistently earlier across all study areas under future weather scenarios (with and without future fuels [Fw_Ff and Fw_Pf respectively]; Figures 4e and 5e).

Effects of future fuels alone (Pw_Ff) on fire regime attributes were comparatively smaller than future weather (Figures 4 and 5), with the exception of the interval between fires, including fires of high intensity where future fuels contributed to increased fire intervals, with the effect most pronounced in fuel-limited systems (Grampians and Adelaide Hills; Figure 5c,d).

The six RCMs produced a wide range of fire regime predictions, but there were some distinct patterns. The RCMs derived from the CSIRO GCM predicted a warmer and drier future across all study

areas, in comparison to the ECHAM group of RCMs, which predicted an even hotter future with limited change to precipitation (Figure S5). The associated impact on the predicted fire regime was that the warmer drier CSIRO climate models typically predicted lower areas burnt, and longer fire intervals compared to predictions derived from the ECHAM models (Figures S6–S10).

3.2 | The role of weather versus fuel

Analysis of the independent and interactive effects of future weather and future fuel indicated consistent effects of weather in all study areas and more variable effects of fuel. Annual area burnt increased, fire intervals decreased, and season midpoints were earlier under predictions of future weather (Figure 6; see Table S3 for marginal and conditional R^2 values).

The role of future fuel was more variable. Area burnt (both annual area burnt and annual area burnt at high intensity) increased under predicted future fuels for the most fuel-limited system (Figure 6). However, the same areas are not always burnt each year, as expressed by the spatial variability in the number of fires across the landscapes (Adelaide hills; Figure S11). For the remaining study areas, the result was more variable and the effect size smaller (Figure 6).

At the two ends of the climate-limited fuel-limited continuum, Adelaide Hills and the Grampians, and East Gippsland, future fuels increased the intervals between fires (Figure 6). There is considerable spatial variation depending on the location within a study area. For example, Adelaide hills under present weather and future fuel predicted average fire intervals of between zero years, that is, multiple fires in 1 year, and 99 years, that is, the maximum fire interval in the simulation (Figure S12). In the middle of the continuum, there was either no clear effect of fuel (Blue Mountains) or future fuels decreased intervals (Alpine and ACT; Figure 6). Future fuels had little effect on fire-season midpoint (Figure 6).

Interactive effects of weather and fuel on fire regime attributes were often only significant at the ends of the climate-limited fuel-limited continuum (Figure 6). The interaction was negative for the most fuel-limited system, Adelaide hills, tempering the increase in area burnt under a combination of both future weather and future fuel, and positive in the most climate-limited system, East Gippsland, increasing the area burnt under the same combination. For fire intervals, only study areas at the more fuel-limited end (Adelaide Hills, Grampians) were predicted to have a negative climate-fuel interaction, reducing the effect of future weather on fire intervals. Interactive effects of weather and fuel on the fire-season midpoint were more variable but consistently minor in all study areas (Figure 6).

4 | DISCUSSION

Shifts in fire regimes in forest landscapes are unlikely to be uniform across temperate Australia. Future weather and fuel will increase

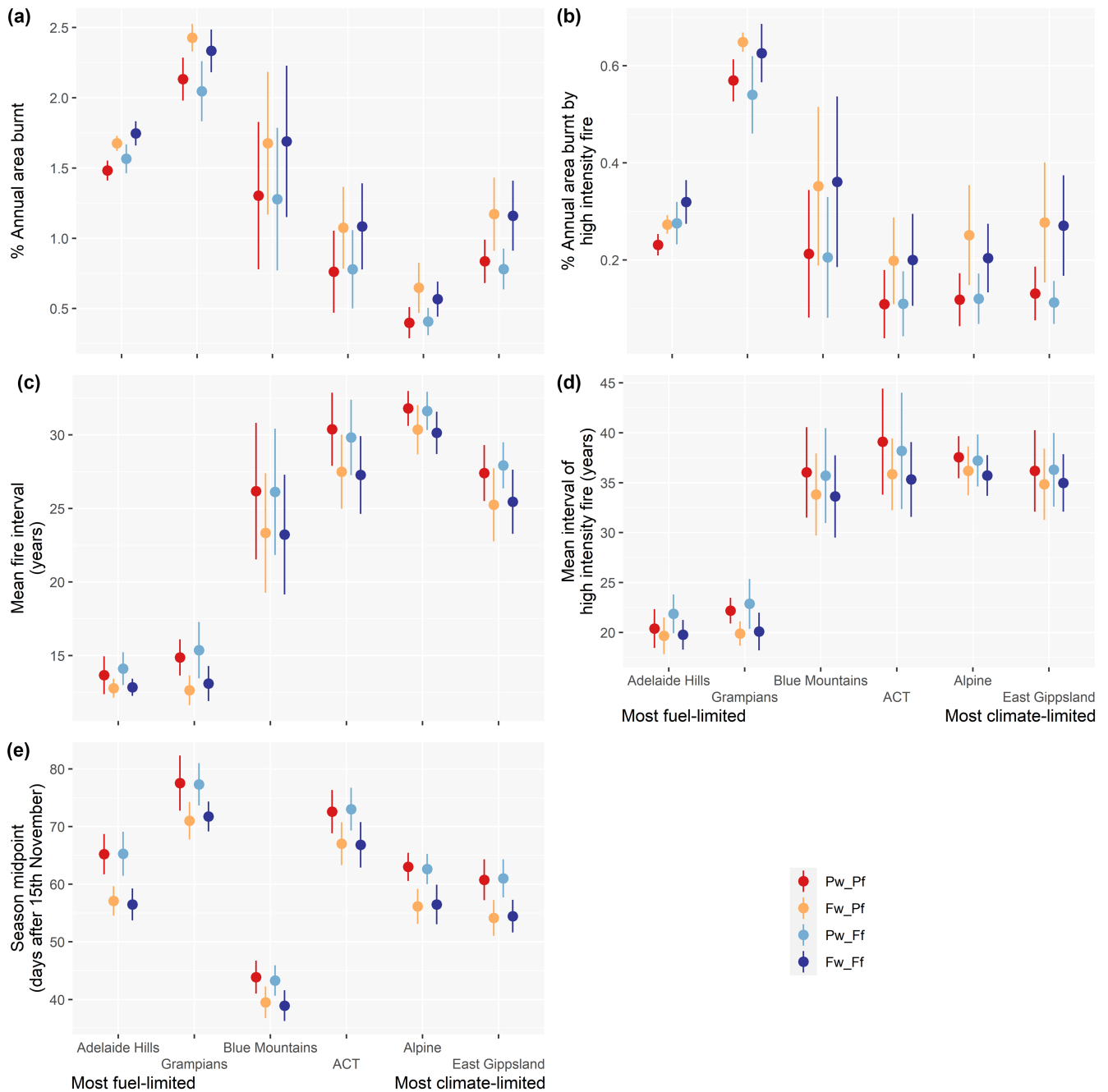


FIGURE 4 Average fire regime attributes by study area ($n = 50$ replicates \times 100 years \times 6 climate models). Study areas from left to right represent the most fuel-limited to the most climate-limited. Errors bars are SD around the mean. Red = present weather and present fuel, yellow = future weather and present fuel, light blue = present weather and future fuel, dark blue = future weather and future fuel. (a) The percent of native vegetation burnt annually, (b) the percent of native vegetation burnt annually at high intensities, (c) mean fire interval in native vegetation, (d) mean high intensity fire interval in native vegetation, and (e) season midpoint.

wildfire extent and intensity, decrease fire interval, and change aspects of the fire season across temperate south-eastern Australia. Future weather had the largest effect, with future fuel acting synergistically or antagonistically with future weather depending on the study area and fire regime attribute of interest. Future weather effects were stronger in climate-limited study areas, and the effects of future fuel were stronger in more fuel-limited study areas.

4.1 | Future changes in fire regimes greater in climate-limited systems

Predicted area burnt was greater and fire intervals shorter in fuel-limited areas compared to climate-limited areas. This is consistent with current patterns of fire in temperate Australia with drier eucalypt woodlands and forests (more fuel-limited)

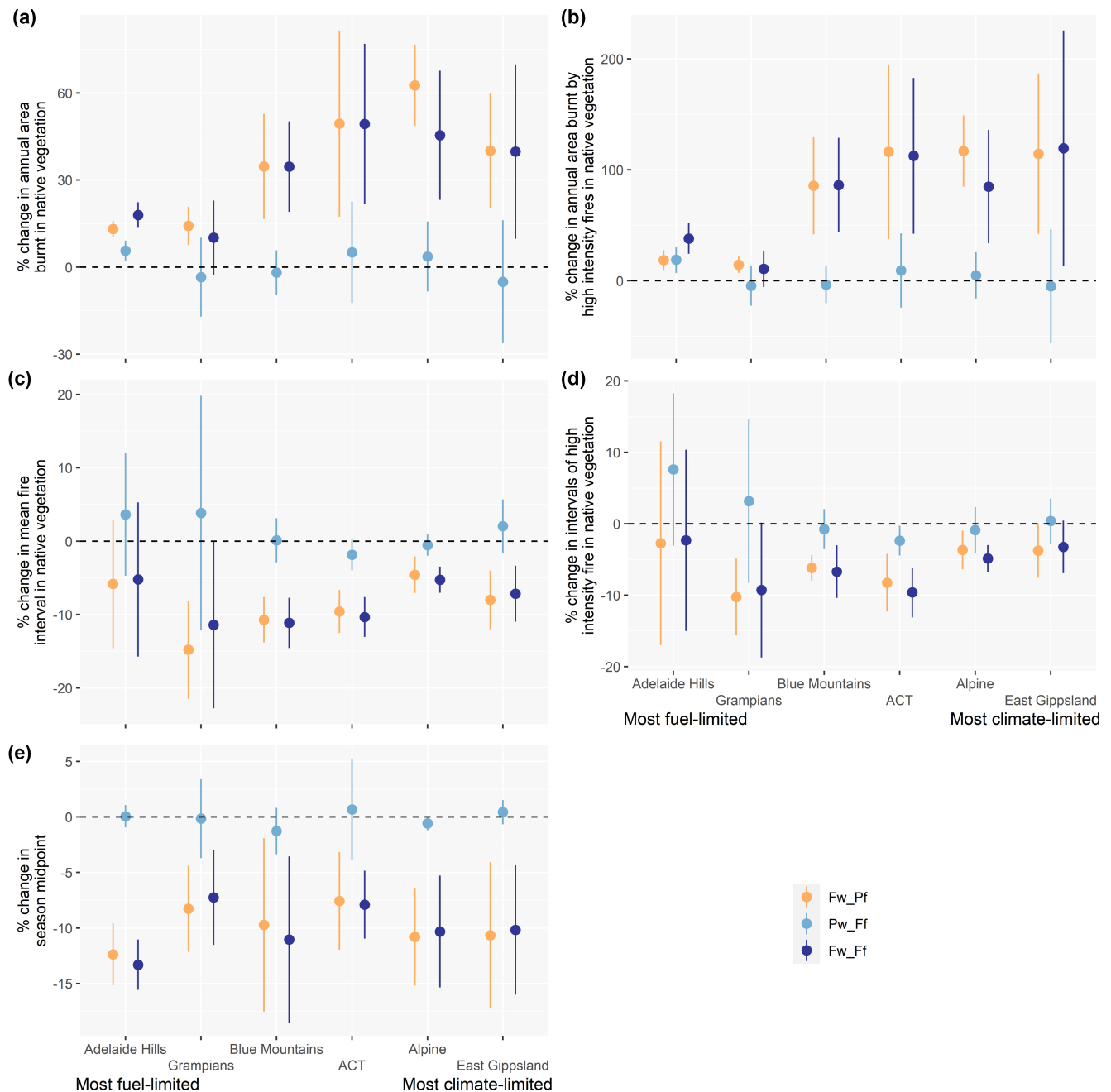


FIGURE 5 Percent change from current conditions (present weather and present fuel, Pw_Pf) for each fire regime attribute by study area ($n = 50$ replicates \times 100 years \times 6 climate models). Study areas from left to right represent the most fuel-limited to the most climate-limited. Errors bars are SD around the mean. Yellow = future weather and present fuel, light blue = present weather and future fuel, dark blue = future weather and future fuel. (a) % change in native vegetation burnt annually, (b) % change in native vegetation burnt annually at high intensities, (c) % change in mean fire interval in native vegetation, (d) % change in mean high intensity fire interval in native vegetation, and (e) % change in season midpoint.

typically being burnt by low-moderate intensity fires every 5–20 years, compared with tall wet eucalypt forests (more climate-limited), which are typically burnt by high-intensity fire every 20–100 years (Murphy et al., 2013). However, the relative changes in fire regime attributes from current to future predictions were generally higher for climate-limited

study areas, particularly for area burnt. These results suggest climate-limited systems have potentially more environmental space for their fire regimes to shift, with comparatively abundant fuels that could increase in flammability through increased aridity (Abatzoglou et al., 2021; Kennedy et al., 2021; Nolan, Blackman, et al., 2020).

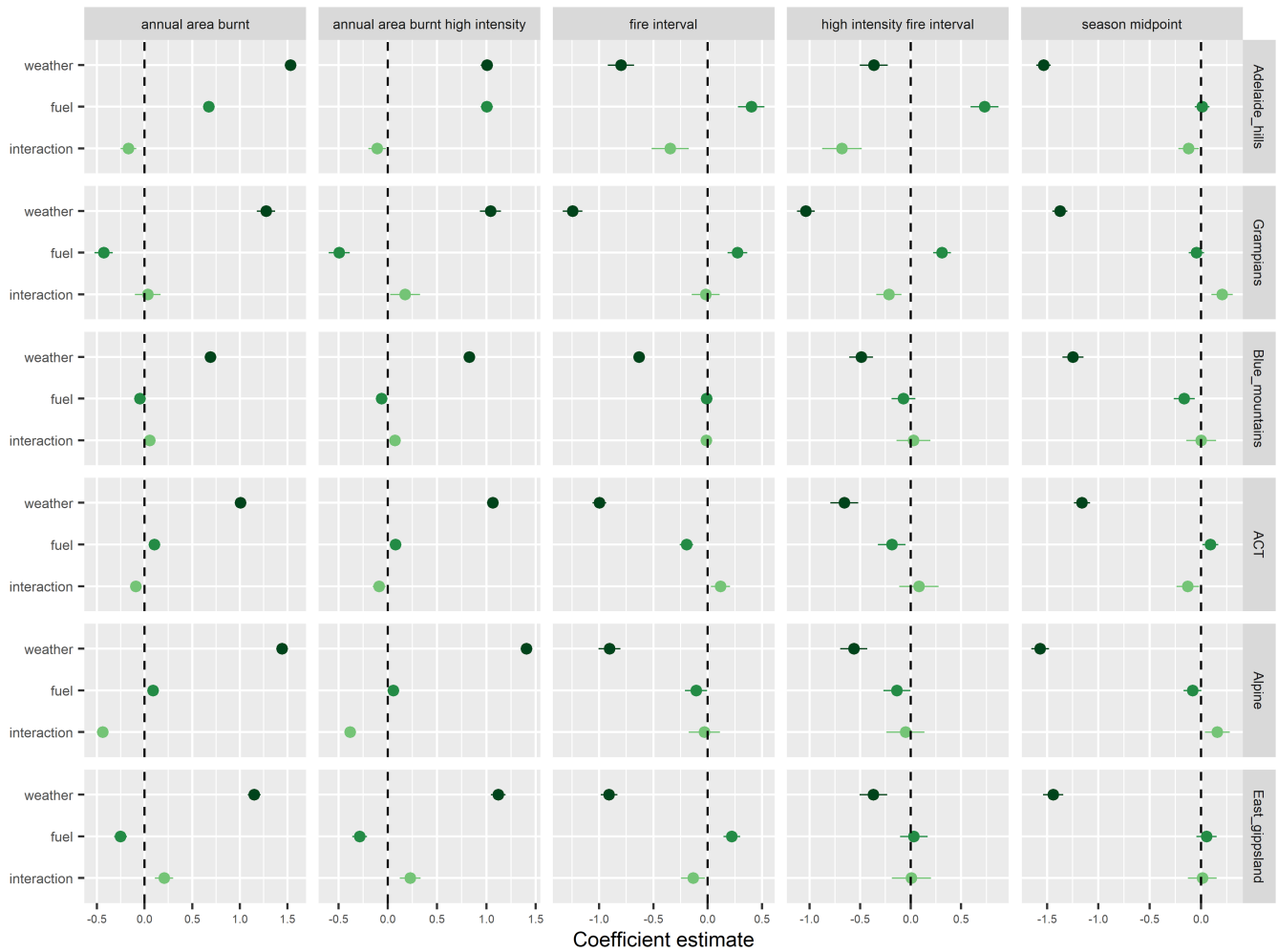


FIGURE 6 Standardized model coefficients (with 95% confidence intervals) for each study area and fire regime attribute. The effect of future weather (dark green), the effect of future fuel (mid green), and the effect of their interaction (light green).

4.2 | Weather had the greatest influence on changes to future fire regimes

Averaged across all climate models, our simulations indicate that future weather rather than future fuels will have greater overall effects on future fire regime attributes. Projecting future fire regimes via predicted direct effects of future climate on fire weather and fuel moisture is a relatively common approach (Balshi et al., 2009; Liu et al., 2010; Nitschke & Innes, 2008; Westerling et al., 2011), and matches the future weather, present fuel (Fw_Pf) scenarios tested in our study. However, while fuel limitations appear to only modestly reduce the projected area burnt at subcontinental scales (Abatzoglou et al., 2021), this may not be the case at all scales and was not seen universally in this study.

There is increasing evidence that contemporary fire-climate relationships may not hold into the future as we move towards the potential for new interactions without historical analogues. One of the biggest limitations in predicting future fire regimes is uncertainty about the degree to which fuel may interact with both fires and climate. The influence of fuel (the indirect influence of climate

combined with time since fire) had contrasting or interacting effects. In climate-limited areas increases in fire weather and ignition likelihood under the warmer and potentially drier conditions are likely to increase area burnt and decrease inter-fire interval due to the increased availability of fuel and occurrence of weather conducive to fire spread. In fuel-limited areas there may be a more variable response depending on the ecosystem, with the structure and flammability of fuel often as important as the amount of fuel (Landesmann et al., 2021). Future climates are predicted to reduce productivity and therefore burnable biomass (Stegen et al., 2011; Zhao & Running, 2010) and these changes may reduce or counteract the direction of changes to the fire regime in all ecosystems.

4.3 | Implications for human and natural values

As increasing wildfire events are correlated with lives lost and house loss (Filkov et al., 2020), the predictions of more fire in all study areas suggests that human lives and assets in temperate Australia will be increasingly exposed to fire under future

climate. While not all fire has negative outcomes for people or the environment (Kolden, 2020), a number of our study areas contain major population centers with complex wildland urban interfaces, making fire management challenging. Prescribed burning is generally used in these areas with an objective of reducing fire risks to people, property, and infrastructure (Penman, Collins, et al., 2020). However, the planned burning treatments have variable efficacy in reducing fire risks and can lead to more fire in the landscape (Cirulis et al., 2020; King et al., 2006; Penman, Clarke, et al., 2020; Price et al., 2015). While our modelling framework focuses on decades long fire regimes, rather than single fire events, evidence from multiple sources points toward more extreme wildfire events in temperate Australia (Duane et al., 2021). The 2019/2020 fire season in south-eastern Australia impacted nearly all of our study's landscapes. This one fire season saw a total of 18,983,588 ha burned, 3113 houses destroyed, and 33 lives lost in 15,344 bushfires (Filkov et al., 2020). Smoke from the bushfires is estimated to be responsible for 417 deaths and thousands of hospitalisations (Borchers Arriagada et al., 2020). Increases in fire regimes as predicted here are likely to have significant implications on people, property, and economic assets.

Predictions of shifts in key fire regime attributes raise several concerns for biodiversity. Fire itself is not problematic for many species in fire-prone ecosystems, however shifts in the fire regime may leave species unable to sustain viable populations (Enright et al., 2015). Fire interval is a key concern for many plant species, with both obligate seeders (species that rely on seed production for regeneration) and resprouters (species that can resprout from buds arising from the stem, branches, or roots) requiring adequate time to restore regenerative capacity before the next fire (Fairman et al., 2019; Turner et al., 2019). However, if we assume that resprouting eucalypt species are more resilient to repeat fires (Collins, 2020), there may be different impacts on eucalypt forest structure and composition depending on their dominance by obligate seeders or resprouters. For example, obligate seeder forests are generally located on wetter, more productive sites, such as those ecosystems at the more climate-limited end of the continuum (Fairman et al., 2016; Vivian et al., 2008). In our study, mean fire interval consistently decreased across all of the study areas. Therefore, the climate-limited systems in our study could be more exposed to potential shifts in species composition due to the higher abundance of obligate seeding species (McColl-Gausden et al., 2022). There are also indications of changes to fire seasonality in our study, with shifts towards an earlier start of up to 10 days in the most fuel-limited study area. Changes to season midpoint suggest seasonality shifts that could potentially influence multiple mechanisms involved in plant persistence like propagule availability and seedling establishment (Miller et al., 2019). Much remains unknown about how changed fire timing and frequency will interact with changes in plant phenological events. Moving forward, conservation emphasis could be placed on species or communities that are already near the edge of their fire regime niche and at risk of extinction (Bowman et al., 2014; Coop et al., 2020; Ratajczak

et al., 2014). Or we could focus on maintaining overall forest or ecosystem resilience to reduce overall impacts if predicted changes to disturbance regimes eventuate (Ingrisch & Bahn, 2018; Johnstone et al., 2016; Keane et al., 2018).

4.4 | Limitations

Our simulation approach is based on a number of assumptions, including that the relationships between fuel variables with climate and time since fire will hold under a changing climate. This is a common assumption in many climate change models, including those that track changes in habitat (Thomas et al., 2004; Thuiller et al., 2006) and fire activity (Archibald et al., 2013; Batllori et al., 2013; Krawchuk et al., 2009; Young et al., 2017). Nonetheless, relationships among fuel, climate, and fire may shift under changing climates, leading to novel interactions (Keeley & Syphard, 2016). Management actions such as active fire suppression and prescribed burning can also influence fuel-climate-fire relationships (Parks et al., 2015), as can exotic invasive species that lead to novel ecosystems (Setterfield et al., 2010; Taylor et al., 2017). While management actions were not accounted for in the scenarios, our study suggests the more fuel-limited study areas have greater scope to mitigate fire impacts through fuel manipulations. This could be of particular importance around wildland urban interfaces where the majority of fire impacts on human values occur. However, the stronger influence of future weather in the climate-limited study areas suggest reduced opportunity for mitigation actions through fuel manipulations alone.

The only anthropogenic factor we considered in this study was the effect of climate change on future fire regimes. Other anthropogenic factors such as population growth from urban centers may increase wildland urban interfaces, therefore exposing more people and property to risk from wildfires. Population growth may also increase fragmentation of vegetation and shift ignition distributions (Pausas & Keeley, 2021). However, increasing ignition rates are unlikely to change the likelihood of large fires (Clarke et al., 2020) as fires in our study areas are rarely limited by ignitions, that is, the ignition 'switch' is nearly always activated (Bradstock, 2010). Changes to fuel profiles resulting from shifts in vegetation through land-use change associated with population growth are possible. However, large portions of our study areas are protected areas of native vegetation that are likely to remain so over the 100-year time horizon of our modelling simulations.

The role of fire feedbacks leading to shifts in species and potentially whole ecosystems was also not examined in our study. Changes to the fire regime combined with direct effects of climate change on species demography such as growth rates and reproduction, can interact to change species population viability (Enright et al., 2015) and thus fuel profiles. Our future research will involve the combined threats of climate and fire regimes shifts on individual species and key functional types by combining our fire regime approach with spatially explicit population viability analysis.

4.5 | Conclusion

Fire activity is predicted to intensify across forested ecosystems from fuel-limited to climate-limited systems. The magnitude of change is highest in the climate-limited areas, which have historically been responsible for fires resulting in the greatest human and environmental impacts (Filkov et al., 2020). These patterns are likely to play out in other forested systems globally and recent extreme fire seasons around the globe strongly support this (Duane et al., 2021). Land managers are unlikely to have the capacity to offset all the predicted changes in fire regimes through fuel manipulations and suppression. We may therefore be forced to accept that intensification of fire regimes in multiple landscapes may be inevitable if climate projections eventuate and therefore plan to reduce associated impacts on multiple assets when and if possible.

ACKNOWLEDGMENTS

This research was supported by an Australian Government Research Training Program (RTP) Scholarship and the Integrated Forest Ecosystem Research agreement between the Victorian Department of Environment, Land, Water and Planning and the University of Melbourne. Regional climate data have been provided by the New South Wales and Australian Capital Territory Regional Climate Model (NARCLiM) project funded by NSW Government Office of Environment and Heritage, University of New South Wales Climate Change Research Centre, ACT Government Environment and Sustainable Development Directorate and other project partners. Open Access publishing facilitated by The University of Melbourne, as part of the Wiley - The University of Melbourne agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST

No conflict of interest declared.

DATA AVAILABILITY STATEMENT

Regional climate data were provided by the NARCLiM project and are freely available: <https://climatechange.environment.nsw.gov.au/Climate-projections-for-NSW>. The modelling data that support the findings of this study are openly available in Dryad at <http://doi.org/10.5061/dryad.0k6djh2m>.

ORCID

Sarah C. McColl-Gausden  <https://orcid.org/0000-0001-7807-8367>

Lauren T. Bennett  <https://orcid.org/0000-0003-2472-062X>

Hamish G. Clarke  <https://orcid.org/0000-0002-8747-3729>

Dan A. Ababei  <https://orcid.org/0000-0001-6482-8999>

Trent D. Penman  <https://orcid.org/0000-0002-5203-9818>

REFERENCES

Abatzoglou, J. T., Battisti, D. S., Williams, A. P., Hansen, W. D., Harvey, B. J., & Kolden, C. A. (2021). Projected increases in western US

forest fire despite growing fuel constraints. *Communications Earth & Environment*, 2, 227.

Abatzoglou, J. T., & Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, 113, 11770–11775.

Abram, N. J., Henley, B. J., Sen Gupta, A., Lippmann, T. J. R., Clarke, H., Dowdy, A. J., Sharples, J. J., Nolan, R. H., Zhang, T., Wooster, M. J., Wurtzel, J. B., Meissner, K. J., Pitman, A. J., Ukkola, A. M., Murphy, B. P., Tapper, N. J., & Boer, M. M. (2021). Connections of climate change and variability large and extreme forest fires in Southeast Australia. *Communications Earth & Environment*, 2, 8.

Albrich, K., Rammer, W., & Seidl, R. (2020). Climate change causes critical transitions and irreversible alterations of mountain forests. *Global Change Biology*, 26, 4013–4027.

Andrews, P., Bevins, C., & Seli, R. C. (2008). *BehavePlus fire modeling system version 4.0 user's guide*. USDA Forest Service.

Archibald, S., Lehmann, C. E. R., Gómez-Dans, J. L., & Bradstock, R. A. (2013). Defining pyromes and global syndromes of fire regimes. *Proceedings of the National Academy of Sciences of the United States of America*, 110, 6442–6447.

Balshi, M. S., McGuire, A. D., Duffy, P., Flannigan, M., Walsh, J., & Melillo, J. (2009). Assessing the response of area burned to changing climate in western boreal North America using a multivariate adaptive regression splines (MARS) approach. *Global Change Biology*, 15, 578–600.

Barbero, R., Abatzoglou, J. T., Pimont, F., Ruffault, J., & Curt, T. (2020). Attributing increases in fire weather to anthropogenic climate change over France. *Frontiers in Earth Science*, 8, Article 104.

Barton, K. (2009). *Mu-MIn: Multi-model inference*. R package version, 1.46.0. <http://R-Forge.R-project.org/projects/mumin/>

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67, 1–48.

Batliori, E., Parisien, M.-A., Krawchuk, M. A., & Moritz, M. A. (2013). Climate change-induced shifts in fire for Mediterranean ecosystems. *Global Ecology and Biogeography*, 22, 1118–1129.

Boer, M. M., Bowman, D., Murphy, B. P., Cary, G. J., Cochrane, M. A., Fensham, R. J., Krawchuk, M. A., Price, O. F., De Dios, V. R., Williams, R. J., & Bradstock, R. A. (2016). Future changes in climatic water balance determine potential for transformational shifts in Australian fire regimes. *Environmental Research Letters*, 11, 065002.

Boer, M. M., Resco De Dios, V., & Bradstock, R. A. (2020). Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, 10, 171–172.

Bond, W. J., & Keeley, J. E. (2005). Fire as a global 'herbivore': The ecology and evolution of flammable ecosystems. *Trends in Ecology & Evolution*, 20, 387–394.

Borchers Arriagada, N., Palmer, A. J., Bowman, D. M., Morgan, G. G., Jalaludin, B. B., & Johnston, F. H. (2020). Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia. *Medical Journal of Australia*, 213, 282–283.

Bowman, D. M. J. S., Murphy, B. P., Neyland, D. L. J., Williamson, G. J., & Prior, L. D. (2014). Abrupt fire regime change may cause landscape-wide loss of mature obligate seeder forests. *Global Change Biology*, 20, 1008–1015.

Bradstock, R., Penman, T., Boer, M., Price, O., & Clarke, H. (2014). Divergent responses of fire to recent warming and drying across South-Eastern Australia. *Global Change Biology*, 20, 1412–1428.

Bradstock, R. A. (2010). A biogeographic model of fire regimes in Australia: Current and future implications. *Global Ecology & Biogeography*, 19, 145–158.

Busby, J. R. (1991). BIOCLIM: A bioclimate analysis and prediction system. *Plant Protection Quarterly*, 6, 8–9.

Caccamo, G., Chisholm, L. A., Bradstock, R. A., & Puotinen, M. L. (2012). Using remotely-sensed fuel connectivity patterns as a

- tool for fire danger monitoring. *Geophysical Research Letters*, 39, L01302.
- Canadell, J. G., Meyer, C. P., Cook, G. D., Dowdy, A., Briggs, P. R., Knauer, J., Pepler, A., & Haverd, V. (2021). Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature Communications*, 12, 6921.
- Cattau, M. E., Wessman, C., Mahood, A., & Balch, J. K. (2020). Anthropogenic and lightning-started fires are becoming larger and more frequent over a longer season length in the U.S.A. *Global Ecology and Biogeography*, 29, 668–681.
- 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, e02211.
- Chong, D., Tolhurst, K. G., Duff, T. J., & Cirulis, B. (2013). *Sensitivity analysis of PHOENIX RapidFire*. BushfireCRC.
- Cirulis, B., Clarke, H., Boer, M., Penman, T., Price, O., & Bradstock, R. (2020). Quantification of inter-regional differences in risk mitigation from prescribed burning across multiple management values. *International Journal of Wildland Fire*, 29, 414–426.
- Clarke, H., & Evans, J. P. (2019). Exploring the future change space for fire weather in southeast Australia. *Theoretical & Applied Climatology*, 136, 513–527.
- Clarke, H., Gibson, R., Cirulis, B., Bradstock, R. A., & Penman, T. D. (2019). Developing and testing models of the drivers of anthropogenic and lightning-caused wildfire ignitions in South-Eastern Australia. *Journal of Environmental Management*, 235, 34–41.
- Clarke, H., Lucas, C., & Smith, P. (2013). Changes in Australian fire weather between 1973 and 2010. *International Journal of Climatology*, 33, 931–944.
- Clarke, H., Penman, T., Boer, M., Cary, G. J., Fontaine, J. B., Price, O., & Bradstock, R. (2020). The proximal drivers of large fires: A pyrogeographic study. *Frontiers in Earth Science*, 8, article 90.
- Clarke, H., Tran, B., Boer, M. M., Price, O., Kenny, B., & Bradstock, R. (2019). Climate change effects on the frequency, seasonality and interannual variability of suitable prescribed burning weather conditions in South-Eastern Australia. *Agricultural and Forest Meteorology*, 271, 148–157.
- Clarke, H. G., Smith, P. L., & Pitman, A. J. (2011). Regional signatures of future fire weather over eastern Australia from global climate models. *International Journal of Wildland Fire*, 20, 550–562.
- Collins, L. (2020). Eucalypt forests dominated by epicormic resprouters are resilient to repeated canopy fires. *Journal of Ecology*, 108, 310–324.
- 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, 659–673.
- Davis, K. T., Dobrowski, S. Z., Higuera, P. E., Holden, Z. A., Veblen, T. T., Rother, M. T., Parks, S. A., Sala, A., & Maneta, M. P. (2019). Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences of the United States of America*, 116, 6193–6198.
- Di Luca, A., Evans, J. P., Pepler, A. S., Alexander, L. V., & Argueso, D. (2016). Evaluating the representation of Australian East Coast lows in a regional climate model ensemble. *Journal of Southern Hemisphere Earth Systems Science*, 66, 108–124.
- Duane, A., Castellnou, M., & Brotons, L. (2021). Towards a comprehensive look at global drivers of novel extreme wildfire events. *Climatic Change*, 165, 43.
- Ellis, T. M., Bowman, D. M. J. S., Jain, P., Flannigan, M. D., & Williamson, G. J. (2021). Global increase in wildfire risk due to climate-driven declines in fuel moisture. *Global Change Biology*, 28, 1544–1559.
- Enright, N. J., Fontaine, J. B., Bowman, D. M., Bradstock, R. A., & Williams, R. J. (2015). Interval squeeze: Altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment*, 13, 265–272.
- Evans, J., Argueso, D., Olson, R., & Di Luca, A. (2017). Bias-corrected regional climate projections of extreme rainfall in south-East Australia. *Theoretical & Applied Climatology*, 130, 1085–1098.
- Evans, J. P., Ji, F., Lee, C., Smith, P., Argüeso, D., & Fita, L. (2014). Design of a regional climate modelling projection ensemble experiment - NARCLiM. *Geoscientific Model Development*, 7, 621–629.
- 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.
- Fairman, T. A., Nitschke, C. R., & Bennett, L. T. (2016). Too much, too soon? A review of the effects of increasing wildfire frequency on tree mortality and regeneration in temperate eucalypt forests. *International Journal of Wildland Fire*, 25, 831–848.
- Filkov, A. I., Ngo, T., Matthews, S., Telfer, S., & Penman, T. D. (2020). Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *Journal of Safety Science and Resilience*, 1, 44–56.
- Finney, M. A. (1998). *FARSITE, fire area simulator-model development and evaluation*. U.S. Dept. of Agriculture Forest Service, Rocky Mountain Research Station.
- Fita, L., Evans, J. P., Argüeso, D., King, A., & Liu, Y. (2017). Evaluation of the regional climate response in Australia to large-scale climate modes in the historical NARCLiM simulations. *Climate Dynamics*, 49, 2815–2829.
- Gill, A. M. (1975). Fire and the Australian flora: A review. *Australian forestry*, 38, 4–25.
- Gill, A. M., & Allan, G. (2008). Large fires, fire effects and the fire-regime concept. *International Journal of Wildland Fire*, 17, 688–695.
- Hagmann, R. K., Hessburg, P. F., Prichard, S. J., Povak, N. A., Brown, P. M., Fulé, P. Z., Keane, R. E., Knapp, E. E., Lydersen, J. M., Metten, K. L., Reilly, M. J., Sánchez Meador, A. J., Stephens, S. L., Stevens, J. T., Taylor, A. H., Yocom, L. L., Battaglia, M. A., Churchill, D. J., Daniels, L. D., ... Waltz, A. E. M. (2021). Evidence for widespread changes in the structure, composition, and fire regimes of western north American forests. *Ecological Applications*, 31, e02431.
- Hanes, C. C., Wang, X., Jain, P., Parisien, M.-A., Little, J. M., & Flannigan, M. D. (2019). Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research*, 49, 256–269.
- Hartig, F. (2020). *DHARMA: Residual diagnostics for hierarchical (multi-level/mixed) regression models*. R package version 0.4.5.
- Harvey, B. J., Donato, D. C., & Turner, M. G. (2016). High and dry: Post-fire tree seedling establishment in subalpine forests decreases with post-fire drought and large stand-replacing burn patches. *Global Ecology and Biogeography*, 25, 655–669.
- Haverd, V., Raupach, M. R., Briggs, P. R., Canadell, J. G., Davis, S. J., Law, R. M., Meyer, C. P., Peters, G. P., Pickett-Heaps, C., & Sherman, B. (2013). The Australian terrestrial carbon budget. *Biogeosciences*, 10, 851–869.
- Higuera, P. E., & Abatzoglou, J. T. (2021). Record-setting climate enabled the extraordinary 2020 fire season in the western United States. *Global Change Biology*, 27, 1–2.
- Hines, F., Tolhurst, K. G., Wilson, A. A., & McCarthy, G. J. (2010). Overall fuel hazard assessment guide. In *Fire and adaptive management* (pp. 1–42). Victorian Government Department of Sustainability and Environment.
- Ingrisch, J., & Bahn, M. (2018). Towards a comparable quantification of resilience. *Trends in Ecology & Evolution*, 33, 251–259.
- IPCC (2007). Summary for policymakers. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change* (pp. 1–21). Cambridge University Press.

- Jackson, S. T., Betancourt, J. L., Booth, R. K., & Gray, S. T. (2009). Ecology and the ratchet of events: Climate variability, niche dimensions, and species distributions. *Proceedings of the National Academy of Sciences of the United States of America*, *106*, 19685–19692.
- Johnstone, J. F., Allen, C. D., Franklin, J. F., Frelich, L. E., Harvey, B. J., Higuera, P. E., Mack, M. C., Meentemeyer, R. K., Metz, M. R., Perry, G. L. W., Schoennagel, T., & Turner, M. G. (2016). Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment*, *14*, 369–378.
- Keane, R. E., Loehman, R. A., Holsinger, L. M., Falk, D. A., Higuera, P., Hood, S. M., & Hessburg, P. F. (2018). Use of landscape simulation modeling to quantify resilience for ecological applications. *Ecosphere*, *9*, e02414.
- Keane, R. E., Mckenzie, D., Falk, D. A., EaH, S., Miller, C., & Kellogg, L.-K. B. (2015). Representing climate, disturbance, and vegetation interactions in landscape models. *Ecological Modelling*, *309–310*, 33–47.
- Keeley, J., & Syphard, A. (2016). Climate change and future fire regimes: Examples from California. *Geosciences*, *6*, 37.
- Kennedy, M. C., Bart, R. R., Tague, C. L., & Choate, J. S. (2021). Does hot and dry equal more wildfire? Contrasting short- and long-term climate effects on fire in the Sierra Nevada, CA. *Ecosphere*, *12*, e03657.
- King, K. J., Cary, G. J., Bradstock, R. A., Chapman, J., Pyrke, A., & Marsden-Smedley, J. B. (2006). Simulation of prescribed burning strategies in south-West Tasmania, Australia: Effects on unplanned fires, fire regimes, and ecological management values. *International Journal of Wildland Fire*, *15*, 527–540.
- Kolden, C. (2020). Wildfires: Count lives and homes, not hectares burnt. *Nature: International Weekly Journal of Science*, *586*, 9.
- Krawchuk, M. A., & Moritz, M. A. (2011). Constraints on global fire activity vary across a resource gradient. *Ecology*, *92*, 121–132.
- Krawchuk, M. A., Moritz, M. A., Parisien, M.-A., Van Dorn, J., & Hayhoe, K. (2009). Global pyrogeography: The current and future distribution of wildfire. *PLoS One*, *4*, e5102.
- Landesmann, J. B., Tiribelli, F., Parisis, J., Veblen, T. T., & Kitzberger, T. (2021). Increased fire severity triggers positive feedbacks of greater vegetation flammability and favors plant community-type conversions. *Journal of Vegetation Science*, *32*, e12936.
- Liu, Y., Stanturf, J., & Goodrick, S. (2010). Trends in global wildfire potential in a changing climate. *Forest Ecology and Management*, *259*, 685–697.
- Loehman, R. A., Keane, R. E., & Holsinger, L. M. (2020). Simulation modeling of complex climate, wildfire, and vegetation dynamics to address wicked problems in land management. *Frontiers in Forests and Global Change*, *3*, article 3.
- McColl-Gausden, S. C., Bennett, L. T., Ababei, D. A., Clarke, H. G., & Penman, T. D. (2022). Future fire regimes increase risks to obligate-seeder forests. *Diversity and Distributions*, *28*, 542–558.
- 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*, 443–455.
- Mcgrattan, K., Hostikka, S., Mcdermott, R., Floyd, J., Weinschenk, C., & Overholt, K. (2013). *Fire dynamics simulator, technical reference guide*. National Institute of Standards and Technology and VTT Technical Research Centre of Finland.
- Mckenzie, D., & Littell, J. S. (2017). Climate change and the ecology of fire: Will area burned increase in a warming western USA? *Ecological Applications*, *27*, 26–36.
- Miller, R. G., Tangney, R., Enright, N. J., Fontaine, J. B., Merritt, D. J., Ooi, M. K. J., Ruthrof, K. X., & Miller, B. P. (2019). Mechanisms of fire seasonality effects on plant populations. *Trends in Ecology & Evolution*, *34*, 1104–1117.
- Montreal Process Implementation Group for Australia, & National Forest Inventory Steering Committee. (2018). *Australia's State of the Forests Report*. ABARES.
- Morgan, P., Heyerdahl, E. K., & Gibson, C. E. (2008). Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. *Ecology*, *89*, 717–728.
- Moritz, M. A., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., Leonard, J., McCaffrey, S., Odion, D. C., Schoennagel, T., & Syphard, A. D. (2014). Learning to coexist with wildfire. *Nature*, *515*, 58–66.
- Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., & Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*, 747–756.
- 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. (2013). Fire regimes of Australia: A pyrogeographic model system. *Journal of Biogeography*, *40*, 1048–1058.
- Mustart, P. J., Rebelo, A. G., Juritz, J., & Cowling, R. M. (2012). Wide variation in post-emergence desiccation tolerance of seedlings of fynbos proteoid shrubs. *South African Journal of Botany*, *80*, 110–117.
- Nitschke, C. R., & Innes, J. L. (2008). Climatic change and fire potential in south-Central British Columbia, Canada. *Global Change Biology*, *14*, 841–855.
- Nolan, R. H., Blackman, C. J., Rescde Dios, V., Choat, B., Medlyn, B. E., Li, X., Bradstock, R. A., & Boer, M. M. (2020). Linking forest flammability and plant vulnerability drought. *Forests*, *11*, 779.
- Nolan, R. H., Boer, M. M., Collins, L., Rescde 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*, 1039–1041.
- Nolan, R. H., Boer, M. M., Resco De Dios, V., Caccamo, G., & Bradstock, R. A. (2016). Large-scale, dynamic transformations in fuel moisture drive wildfire activity across southeastern Australia. *Geophysical Research Letters*, *43*, 4229–4238.
- Olson, J. S. (1963). Energy storage and the balance of producers and decomposers in ecological systems. *Ecology*, *44*, 322–331.
- Olson, R., Evans, J. P., Di Luca, A., & Argüeso, D. (2016). The NARCIIM project: Model agreement and significance of climate projections. *Climate Research*, *69*, 209–227.
- Parks, S. A., & Abatzoglou, J. T. (2020). Warmer and drier fire seasons contribute to increases in area burned at high severity in Western US forests from 1985 to 2017. *Geophysical Research Letters*, *47*, e2020GL089858.
- Parks, S. A., Miller, C., Abatzoglou, J. T., Holsinger, L. M., Parisien, M.-A., & Dobrowski, S. Z. (2016). How will climate change affect wildland fire severity in the western US? *Environmental Research Letters*, *11*, 035002.
- Parks, S. A., Miller, C., Parisien, M.-A., Holsinger, L. M., Dobrowski, S. Z., & Abatzoglou, J. (2015). Wildland fire deficit and surplus in the western United States, 1984–2012. *Ecosphere*, *6*, 1–13.
- Pausas, J. G. (2004). Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean Basin). *Climatic Change*, *63*, 337–350.
- Pausas, J. G., & Keeley, J. E. (2009). A burning story: The role of fire in the history of life. *BioScience*, *59*, 593–601.
- Pausas, J. G., & Keeley, J. E. (2021). Wildfires and global change. *Frontiers in Ecology and the Environment*, *19*, 387–395.
- Penman, T., Collins, L., Duff, T., Price, O., & Cary, G. (2020). Scientific evidence regarding effectiveness of prescribed burning. In W. M. Leavesley & R. Thornton (Eds.), *Prescribed burning in Australasia: The science, practice and politics of burning the bush* (pp. 99–116). Australasian Fire and Emergency Services Council.
- Penman, T. D., Ababei, D., Chong, D. M. O., Duff, T. J., & Tolhurst, K. G. (2015). A fire regime risk management tool. In J. Sharples (Ed.), *21st international congress on modelling and simulation*, Gold Coast, Australia, 29 Nov to 4 Dec 2015 (pp. 270–276). www.mssanz.org.au/modsim2015

- Penman, T. D., Clarke, H., Cirulis, B., Boer, M. M., Price, O. F., & Bradstock, R. A. (2020). Cost-effective prescribed burning solutions vary between landscapes in eastern Australia. *Frontiers in Forests and Global Change*, 3, article 79.
- Penman, T. D., Collins, L., Price, O. F., Bradstock, R. A., Metcalf, S., & Chong, D. M. O. (2013). Examining the relative effects of fire weather, suppression and fuel treatment on fire behaviour – A simulation study. *Journal of Environmental Management*, 131, 325–333.
- Perera, A. H., Sturtevant, B. R., & Buse, L. J. (2015). *Simulation modeling of forest landscape disturbances*. Springer.
- Pitman, A. J., Narisma, G. T., & Mcaneney, J. (2007). The impact of climate change on the risk of forest and grassland fires in Australia. *Climatic Change*, 84, 383–401.
- Price, O. F., Pausas, J. G., Govender, N., Flannigan, M., Fernandes, P. M., Brooks, M. L., & Bird, R. B. (2015). Global patterns in fire leverage: The response of annual area burnt to previous fire. *International Journal of Wildland Fire*, 24, 297–306.
- R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.
- Ratajczak, Z., Nippert, J. B., & Ocheltree, T. W. (2014). Abrupt transition of Mesic grassland to shrubland: Evidence for thresholds, alternative attractors, and regime shifts. *Ecology*, 95, 2633–2645.
- Setterfield, S. A., Rossiter-Rachor, N. A., Hutley, L. B., Douglas, M. M., & Williams, R. J. (2010). Turning up the heat: The impacts of *Andropogon gyanus* (Gamba grass) invasion on fire behaviour in northern Australian savannas. *Diversity & Distributions*, 16, 854–861.
- Sheth, S. N., & Angert, A. L. (2018). Demographic compensation does not rescue populations at a trailing range edge. *Proceedings of the National Academy of Sciences of the United States of America*, 115, 2413–2418.
- Steel, Z. L., Collins, B. M., Sapsis, D. B., & Stephens, S. L. (2021). Quantifying pyrodiversity and its drivers. *Proceedings of the Royal Society B: Biological Sciences*, 288, 20203202.
- Stegen, J. C., Swenson, N. G., Enquist, B. J., White, E. P., Phillips, O. L., Jørgensen, P. M., Weiser, M. D., Monteagudo Mendoza, A., & Núñez Vargas, P. (2011). Variation in above-ground forest biomass across broad climatic gradients. *Global Ecology and Biogeography*, 20, 744–754.
- Stephens, S. L., Burrows, N., Buyantuyev, A., Gray, R. W., Keane, R. E., Kubian, R., Liu, S., Seijo, F., Shu, L., Tolhurst, K. G., & van Wagtenonk, J. W. (2014). Temperate and boreal forest megafires: Characteristic and challenges. *Frontiers in Ecology and the Environment*, 12, 115–122.
- Suppiah, R., Hennessy, K. J., Whetton, P. H., McInnes, K., Macadam, I., Bathols, J., Ricketts, J., & Page, C. M. (2007). Australian climate change projections derived from simulations performed for the IPCC 4th assessment report. *Australian Meteorological Magazine*, 56, 131–152.
- Taylor, K. T., Maxwell, B. D., Mcwethy, D. B., Pauchard, A., Nuñez, M. A., & Whitlock, C. (2017). *Pinus contorta* invasions increase wildfire fuel loads and may create a positive feedback with fire. *Ecology*, 98, 678–687.
- Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., Erasmus, B. F. N., Ferreira de Siqueira, M., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A. S., Midgley, G. F., Miles, L., Ortega-Huerta, M. A., Townsend Peterson, A., Phillips, O. L., & Williams, S. E. (2004). Extinction risk from climate change. *Nature*, 427, 145–148.
- Thuiller, W., Lavorel, S., Sykes, M. T., & Araújo, M. B. (2006). Using niche-based modelling to assess the impact of climate change on tree functional diversity in Europe. *Diversity and Distributions*, 12, 49–60.
- Tolhurst, K., Shields, B., & Chong, D. (2008). Phoenix: Development and application of a bushfire risk management tool. *The Australian Journal of Emergency Management*, 23, 47–54.
- Turner, M. G., Braziunas, K. H., Hansen, W. D., & Harvey, B. J. (2019). Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. *Proceedings of the National Academy of Sciences of the United States of America*, 116, 11319–11328.
- Tymstra, C., Flannigan, M. D., Armitage, O. B., & Logan, K. (2007). Impact of climate change on area burned in Albertas boreal forest. *International Journal of Wildland Fire*, 16, 153–160.
- Viscarra Rossel, R. A., Chen, C., Grundy, M. J., Searle, R., Clifford, D., & Campbell, P. H. (2015). The Australian three-dimensional soil grid: Australia's contribution to the GlobalSoilMap project. *Soil Research*, 53, 845–864.
- Vivian, L. M., Cary, G. J., Bradstock, R. A., & Gill, A. M. (2008). Influence of fire severity on the regeneration, recruitment and distribution of eucalypts in the Cotter River catchment, Australian Capital Territory. *Austral Ecology*, 33, 55–67.
- Westerling, A. L. (2016). Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions: Biological Sciences*, 371, 1–10.
- Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase Western U.S. Forest Wildfire Activity. *Science*, 313, 940–943.
- Westerling, A. L., Turner, M. G., Eah, S., Romme, W. H., & Ryan, M. G. (2011). Continued warming could transform greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences of the United States of America*, 108, 13165–13170.
- Young, A. M., Higuera, P. E., Duffy, P. A., & Hu, F. S. (2017). Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography*, 40, 606–617.
- Zhao, M., & Running, S. W. (2010). Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, 329, 940–943.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: McColl-Gausden, S. C., Bennett, L. T., Clarke, H. G., Ababei, D. A., & Penman, T. D. (2022). The fuel–climate–fire conundrum: How will fire regimes change in temperate eucalypt forests under climate change?. *Global Change Biology*, 28, 5211–5226. <https://doi.org/10.1111/gcb.16283>