Projected changes in Australian fire regimes during the 21st century and consequences for ecosystems


It is advisable to refer to the publisher's version if you intend to cite from the work. See Guidance on citing.

To link to this article DOI: http://dx.doi.org/10.1071/WF16032

Publisher: CSIRO

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the End User Agreement.

www.reading.ac.uk/centaur
CentAUR
Central Archive at the University of Reading
Reading’s research outputs online
Projected changes in Australian fire regimes during the 21\textsuperscript{st} century and consequences for ecosystems

Harrison, S.P.\textsuperscript{1,2} and Kelley, D.I.\textsuperscript{1,2}

\textsuperscript{1} School of Biological Sciences, Macquarie University, North Ryde, NSW 2109, Australia.
\textsuperscript{2} School of Archaeology, Geography \& Environmental Sciences, Reading University, Whiteknights, Reading, RG6 6AH, UK

Corresponding author: Sandy P. Harrison (s.p.harrison@reading.ac.uk)

Ms for: International Journal of Wildland Fire

Revised Version: 6\textsuperscript{th} February 2016

Abstract: Climate projections show Australia becoming significantly warmer during the 21\textsuperscript{st} century, while precipitation decreases over much of the continent. Such changes are generally considered to increase wildfire risk. Nevertheless, using a process-based model of vegetation dynamics and vegetation–fire interactions, we show that while burnt area increases in southern and central Australia, it decreases in northern Australia. Overall the projected increase in fire by the end of the 21\textsuperscript{st} century is small (0.7–1.3\% of land area equivalent to 12–24\% of current burnt area, depending on the climate scenario). The direct effects of increasing CO\textsubscript{2} on vegetation productivity and water-use efficiency influence simulated fire regimes: CO\textsubscript{2} effects tend to increase burnt area in arid regions, but increase vegetation density and reduce burnt area in forested regions. Increases in fire promotes a shift to more fire-adapted trees in wooded areas and their encroachment into grasslands, with an overall increase in forested area of 3.9–11.9\% of land area by the end of the century. The decrease in fire in northern Australia leads to an increase in tree cover (ca 20\%) and an expansion of tropical forest. Thus, although the overall change in burnt area is small it has noticeable consequences for vegetation patterns across the continent.

Non-specialist summary: Simulations show decreased fire in northern Australia and increased fire in central and southern Australia in response to projected changes in 21\textsuperscript{st} century climate. Climate-induced vegetation changes are as important as climate in determining future fire regimes. Changes in fire regime are large enough to cause changes in vegetation patterns.

Additional keywords: resprouting vegetation, fire-induced vegetation changes, fire danger, CO\textsubscript{2} impacts on fire, fuel limitation, biome shifts

Running head: Future fire regimes in Australia
Introduction

Around 5% (0.41 M km$^2$) of the Australian continent burns annually, and all but the most arid parts of the continent are susceptible to periodic fire (Bradstock et al. 2012; Hughes and Steffen 2013; Murphy et al. 2013). Fire frequency is particularly high in the tropical savannas of northern Australia (1-5 years) although the intensity of these fires is relatively low, whereas more intense but less frequent (>100 years) fires are characteristic of the forests of eastern Australia. Fires are relatively frequent (1-10 years) in woodlands in the continental interior, but become increasingly rare towards the arid regions because of fuel limitation (Murphy et al. 2013). Much of the Australian vegetation is adapted to fire through strategies that promote rapid re-establishment from seed or recovery through resprouting (Lawes et al. 2011; Bradstock et al. 2012; Clarke et al. 2013).

Nevertheless, changes in fire regimes are of concern both because of the rapidly escalating social and economic costs (Crompton and McAneney 2008; Ashe et al. 2008; Stephenson et al. 2012; Hughes and Steffen 2013) and because of the potential impacts on vegetation and biodiversity (Bradstock 2008; Williams et al. 2009; Gill 2012).

Climate projections for the 21st century (Collins et al. 2013; Kirtman et al. 2013) show significant warming over Australia, with decreased precipitation in many regions. Warmer and drier conditions are generally considered to increase in the risk of fire in Australia (Williams et al. 2001; Hennessy et al. 2005; Lucas et al. 2007; Pitman et al. 2007; Fox-Hughes et al. 2014). However, increased fire risk does not necessarily translate into increased burning in situations where the climate changes reduce vegetation productivity and hence fuel loads (Harrison et al. 2010; Bistinas et al. 2014; Higuera et al. 2015; Knorr et al. 2016a, b). Indeed, statistical modelling suggests either a reduction (Krawchuk et al. 2009) or only a moderate increase (Moritz et al. 2012) in fire in Australia. The reliability of these projections is compromised because they do not account for the impact of changing CO$_2$ concentrations on vegetation productivity and water-use efficiency or for potential changes in vegetation distribution and their impact on fire regimes under a changing climate. Both of these effects are included in process-based dynamic global vegetation models (DGVMs).

Here, we use the LPX-Mv1 DGVM (Kelley et al. 2014) driven by outputs from nine coupled ocean-atmosphere models forced using two different future scenarios of changes in atmospheric composition and land use from the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012), to examine potential changes in Australian fire regimes over the 21st century and the implications of these changes for natural vegetation patterns.
Methods

Study Area

Australia spans 29° of latitude, with a temperature gradient from tropical in the north to temperate in the south. Much of the continent is arid or semi-arid. Precipitation regimes reflect the seasonal migration of the subtropical anticyclone belt (Sturman and Tapper, 1996). Most of the north is influenced by southeasterly trade winds in winter and monsoonal flow in summer, and hence has highly seasonal rainfall with dry winters and wet summers. The central interior, dominated by travelling anticyclones throughout the year, is dry. Troughs between the travelling anticyclones entrain maritime northwesterly airflows, bringing summer rain to parts of the east coast and southern highlands. Southern Australia, dominated by travelling anticyclones in summer and westerly winds in winter, has winter rainfall and relatively dry summers. Much of northern and eastern Australian experiences considerable inter-annual variability in precipitation, associated with the El Nino-Southern Oscillation.

The natural vegetation of Australia follows a structural continuum reflecting these rainfall patterns (Groves 1994). Closed forests are distributed discontinuously along the east coast from northeastern Queensland to western Tasmania, in regions with year-round rainfall. Tall, relatively open forests occur throughout coastal and montane southeastern Australia and in southwestern Australia, in sub-humid sites with either summer or winter rainfall. Woodlands occupy drier areas inland, wherever rainfall is sufficient regardless of source or season. Mallee shrubland occurs in areas of southern Australia with a long dry season but where westerly flow brings rain in winter. The arid interior is largely characterized by shrubland and tussock grass.

Fire plays a major role in shaping Australian vegetation patterns, and many plants show adaptations to fire (Lawes et al. 2011; Bradstock et al. 2012; Clarke et al. 2013). The different climate regimes and vegetation types give rise to different fire regimes across the continent (Murphy et al. 2013). Most of the closed forests in eastern Australia burn infrequently, but when fires do occur in hot, dry years the abundance of fuel leads to high intensity ground and crown fires. In the continental interior, aridity prevents the build-up of high fuel loads, limiting both the occurrence and intensity of fires. The seasonal precipitation regime in northern Australia allows fuel accumulation in the wet season and promotes rapid fuel drying in winter. This results in frequent fires, but their regularity prohibits the fuel build up and thus these fires are generally of low intensity. Seasonal precipitation regimes in southern Australia are often characterised by high interannual variability, and this leads to more unpredictable fire seasons than in northern Australia. The role of fuel loads in creating the...
diversity of fire regimes across the continent provides a major justification for using process-based
modelling to investigate the impacts of climate change on fire regimes.

The Model and Modelling Approach.

We use the LPX-Mv1 fire-enabled DGVM (Kelley et al. 2014) to simulate the response of
Australian fire regimes and vegetation to climate changes resulting from two scenarios of 21st
century changes in atmospheric composition and land use. We use outputs from multiple coupled
ocean-atmosphere models driven by these two scenarios to encompass the range of potential
responses to each scenario. LPX-Mv1 (Kelley et al. 2014) was developed from the LPX DGVM
(Prentice et al. 2011); the vegetation dynamics component of LPX was based on the Lund-Potsdam-
Jena (LPJ) DGVM (Sitch et al. 2003). The model simulates vegetation and fire properties on a
spatial grid of 0.5 by 0.5°; it does not simulate spatially explicit distributions within a grid cell.

Vegetation within a grid cell is described in terms of fractional coverage of PFTs, defined by life
form (tree, grass), with grasses further subdivided by photosynthetic pathway (C3, C4) and trees by
bioclimatic tolerance (tropical, temperate, boreal), leaf type, (broadleaf, needleleaf), and
phenological response to drought or cold (evergreen or deciduous). LPX-Mv1 differs from LPX by
including resprouting and non-resprouting variants of tropical broadleaf evergreen trees, tropical
broadleaf deciduous trees, temperate broadleaf evergreen trees and temperate broadleaf deciduous
trees. Climatic tolerance limits determine whether a PFT could occur in a grid cell. Establishment
rates are dependent on the area available for colonization, except that resprouting PFTs have lower
establishment rates than non-resprouting PFTs. The abundance of each PFT is determined through
competition, as a function of PFT-specific productivity. Gross primary production is calculated for
each PFT using an explicit photosynthesis model and full accounting of the water and energy
exchanges between vegetation and the atmosphere (Sitch et al. 2003). Transpiration, and therefore
GPP, is limited if available moisture is less than the maximum demand. Atmospheric CO2
concentration affects the water cost per unit production. Net Primary Production (NPP) is calculated
after accounting for maintenance and growth respiration, and allocated in fixed proportions to roots,
leaves and woody tissues.

The dynamic vegetation component of the model provides information on vegetation type and
productivity that is then used to specify fuel loads in the fire component of the model. Woody
material contributes to coarse fuel, while leaves and grass contribute to fine fuel loads (Figure 1).
The soil moisture accounting scheme in the vegetation component is used to predict the moisture
content of live fuel. Vegetation information is passed to the fire module once a year.
The fire module in LPX-Mv1 represents the influence of potential ignition rates, vegetation properties and weather conditions on biomass burning through explicit formulations of the probability of fires starting, their rate of spread, fire intensity and the amount of fuel combusted, and the consequences for the mortality and regeneration of different PFTs. The model simulates multiple aspects of the fire regime (number of fires, fire type, intensity, frequency and burnt area), and changes in these characteristics influence vegetation composition.

Fire is explicitly simulated in each grid cell on a daily time-step. This temporal resolution means that the model is adapted to using daily mean climate conditions as inputs; it does not take account of sub-daily or short-lived extreme conditions such as wind gusts. The number of fire starts is a function of lightning ignitions and fire susceptibility (Figure 1). LPX-Mv1 does not include human ignitions. While human ignitions affect the number and seasonality of fires (Russell-Smith et al. 2007; Archibald et al. 2013), they have little effect on burnt area (Bistinas et al. 2014; Knorr et al. 2014; Knorr et al. 2016a). LPX-Mv1 allows the fraction of ground strikes to vary spatially and seasonally, realistically partitions strike distribution between wet and dry days, and has a variable number of strikes on dry days (Kelley et al. 2014). Fire susceptibility takes into account the amount, properties and moisture content of the available fuel load. There are four fuel size classes: 1 hour or fine fuel (derived from leaves and grass), and 10 hour (from small branches), 100 hour (from large branches) and 1000 hour (from boles and trunks) fuels. The size class determines the rate at which fuel moisture equilibrates to relative humidity on dry days. Ignitions do not result in a fire unless the combined load of 1, 10 and 100 hour fuel is greater than 200 g/m², a surrogate for minimal fuel continuity (Thonicke et al. 2001). Fuel loads can be reduced through fire or decomposition, where coarse and fine fuels decompose at different rates (Brovkin et al. 2012).

Fire spread, intensity and residence time are dependent on wind speed and fuel moisture (Figure 1), and calculated using the Rothermel equations (Rothermel 1972). Fires are assumed to be elliptical and fire size is therefore calculated using a simple geometric relationship with rate of spread. Wind speed is modulated by vegetation type and density, as measured by foliar projective cover. Burnt area is calculated as the product of the number of fires and fire spread.

Mortality occurs through crown scorching and cambial death, where cambial damage is determined by fire intensity and residence time in relation to the bark thickness of woody vegetation. In LPX-Mv1, the PFT-specific bark thickness is specified as a range when new populations establish. Fires will preferentially remove thin-barked trees, leading to a change in average bark thickness as a
consequence of fire history (Kelley et al. 2014). Resprouting PFTs survive fires if there is unconsumed above-ground biomass; plant size and productivity after resprouting is, however, reduced in proportion to the amount of biomass consumed.

Given its spatial and temporal resolution, LPX-Mv1 is particularly well adapted to simulate regional-scale changes in burnt area, the aspect of the fire regime that is important for carbon cycle and climate feedbacks, in response to changes in climate. The 21st century LPX-Mv1 simulations are idealized experiments focusing on the impact of climate and CO₂ changes on vegetation and fire regimes. They do not account for potential future changes in the number of lightning strikes or in anthropogenic fire suppression. There is no convincing evidence for changes in thunderstorm frequency over the late 20th century (Hartmann et al. 2013) and estimates of the change in lightning flash rate with future warming vary considerably (Williams 1992; Price and Rind 1994; Michalon et al. 1999; Romps et al. 2014). Furthermore, sensitivity analyses show that changes in the number of strikes has relatively little effect on burnt area compared to the impact of changing weather conditions on the probability that a strike will cause ignition (Kelley et al. 2014). Anthropogenic landscape fragmentation significantly reduces fire spread and hence burnt area (Bistinas et al. 2014; Knorr et al. 2014) but is not included in the 21st century simulations because projected changes in land use are highly uncertain.

Input Data

The daily climate data required for the fire module are calculated in the model by linear interpolation between the monthly values for each variable assigned to the mid-point of each month. Monthly maximum and minimum temperature, precipitation, cloud cover, and number of wet days were obtained from the CRU TS3.1 data set (Harris et al. 2013) and monthly wind speed from the National Center for Environmental Prediction (NCEP) reanalysis data set (Kalnay et al. 1996). The model includes a weather generator (Geng et al., 1998) which allocates precipitation to wet days taking account of persistence in dry and wet conditions, and distributes the observed monthly precipitation to wet days using an empirically-based function of rainfall distribution such that the amount of rain falling on each wet day is different. A seasonal climatology of lightning ignitions is calculated from the High Resolution Monthly Climatology of lightning flashes from the Lightning Imaging Sensor–Optical Transient Detector (LIS/OTD) data set (http://gcmd.nasa.gov/records/GCMD_lohrmc.html). Atmospheric CO₂ concentration is prescribed annually as a single global value from observations (http://www.esrl.noaa.gov/gmd/).
The model was spun up (Table 1) using constant CO$_2$ (286ppm) and detrended climate data until the carbon pools were in equilibrium. The detrended climate data was obtained by regressing the annual average values for all climate variables for the period 1950-2000 on each grid cell and removing the value estimated for the slope of this regression from the monthly data. The historical run (Table 1) used transient CO$_2$ from 1850 onwards. The detrended climate data were used until time-varying data are available, i.e. after 1948 for wind speed and from 1901 onwards for all other climate variables (Table 1).

LPX-Mv1 was run from 2006 to 2100 using climate realizations from nine coupled ocean-atmosphere climate models (Table 2) forced by two alternative Representative Concentration Pathway (RCP) scenarios (van Vuuren et al. 2011): RCP4.5 and RCP8.5. Lightning ignitions are prescribed as in the historic simulation. However, since the number of dry-day strikes is determined by number of wet days per month, the interannual variability in the number of dry strikes is different in the future simulations from in the historic period. LPX-Mv1 is also driven by atmospheric CO$_2$, which changes in the RCP4.5-driven simulations from 380.8 to 576 ppm by 2080 CE and stabilises thereafter. In the RCP8.5 simulations, CO$_2$ concentrations increase continuously to reach 1231 ppm by 2100. To examine the direct impact of increasing CO$_2$ on vegetation productivity and water-use efficiency, we made additional simulations in which climate varied but CO$_2$ was held constant at the 2006 level of 380.8 ppm (fixed-CO$_2$ experiment).

Model Evaluation

The historic simulation was evaluated by comparing simulated and observed vegetation distribution (DeFries and Hanson 2009), fine litter production, as a surrogate for fuel load (Vegetation And Soil-carbon Transfer, VAST, data set: Barrett 2001), carbon (Ruesch and Gibbs 2008), and burnt area and timing of the fire season (GFED4: Giglio et al. 2013). The simulations do not take account of land-use changes, so cropland areas were masked out (using the GLC2000 5x5’ land cover map: Bartholomé and Belward 2005) in making these comparisons.

We used benchmarking metrics where performance is expressed relative to a mean and random model for each variable (Kelley et al. 2013) to evaluate the realism of the simulations. We use the normalized mean error (NME) to account for geographic patterning in comparisons of total values and annual averages; these scores provide a description of the spatial error of the model (Table 3). The NME takes the value zero when agreement is perfect, unity when agreement is equal to that expected when the mean value of all observations is substituted for the model, and values > 1 when the model’s performance is worse than the null model. We use the Manhattan Metric (MM) for
measures of relative abundance (i.e. where the sum of items in each grid cell must be equal to one, e.g. for vegetation cover). MM takes the value 0 for perfect agreement, and 2 for complete disagreement. Temporal differences in the timing of the fire season were assessed by calculating the mean phase difference (MPD, Table 3) in months between observation and simulations, where 0 indicates perfect agreement and 1 perfect disagreement in timing.

Two null models were constructed for each benchmark to facilitate interpretation of the metric scores (Table 3). The “mean null model” compares each benchmark to a data set of the same size, filled with the mean of the observations. The “random null model” is constructed by creating a data set of the same dimensions as the benchmark data set by bootstrap resampling of the observations, using 1,000 randomizations to estimate a probability density function of the scores.

**Analyses of future fire**

We examine the 21st century changes in vegetation and fire, focusing on burnt area, for the continent as a whole and for regions where there is a consistent signal in the direction of the simulated change in burnt area during the 21st century. We defined four regions for this second analysis: northern Australia (north of 17° S), central Australia (between 24 and 35° S and 124 and 148° E), southeastern Australia (the area lying to the southeast of the line joining 32° S, 153° E and 38° S, 141° E) and southwestern Australia (the area southwest of the line joining 25° S, 113°E and 33° S, 124°E).

Ensemble averages of the LPX-Mv1 outputs were created by simple averaging of the results of individual simulations for each of the RCP scenarios, with and without changes in CO₂ (RCP4.5 varying-CO₂, RCP4.5 fixed-CO₂, RCP8.5 varying-CO₂, RCP8.5 fixed-CO₂). The robustness of the simulated changes is assessed by the agreement between models, while significance is measured by the strength of the change relative to interannual variability in the historic period (1997-2006).

Changes in vegetation are assessed in terms of the abundance of individual PFTs and as shifts in major vegetation types (biomes). We convert the simulated abundance of individual PFTs to biomes using a version of the algorithm described in Prentice et al. (2011), in which the boundaries between biomes are defined by the presence/absence of specific PFTs and the absolute amounts of tree cover. We define five biomes: grassland and shrubland, sclerophyll woodland, temperate forest, tropical savanna, and tropical forest. We distinguish tropical biomes (tropical savanna, tropical forest) by the presence of either tropical broadleaf evergreen trees or tropical broadleaf deciduous
trees. The boundary between shrubland and woodland is set at 2% tree cover and that between woodland and forest at 60% tree cover.

Results

3.1. Simulation of present-day vegetation properties and fire regimes

LPX-Mv1 reproduces the observed pattern of tree and grass abundance reasonably well, though there is less woody vegetation in northern Australia and more in southeastern Australia than observed (Figure 2; Table 3). Although the model underestimates the amount of woody vegetation (Table 3), transitions from forest through woodland/savanna to grassland in northern and eastern Australia are well captured. LPX-Mv1 reproduces the changing abundance of resprouters and non-resprouters with increasing aridity and post-fire vegetation recovery rates at sites where this has been measured (Kelley et al., 2014). Vegetation productivity (NPP) is close to observationally constrained estimates of NPP during the recent decade (Table 3: 2191 Tg C yr\(^{-1}\) compared to observed values of 2210 ± 398 Tg C yr\(^{-1}\): Haverd et al., 2013). The model captures the first-order geographic patterns in biomass (Table 3); the largest discrepancies are in areas where tree cover is underestimated. Similarly, the model simulates fine-fuel production comparable to observed values (Table 3: simulated mean 202g/m\(^2\)/yr compared to observed mean values of 230 g/m\(^2\)/yr). Benchmark metrics show LPX-Mv1 performs much better than the mean and randomly-resampled models for most vegetation properties (Table 3).

LPX-Mv1 reproduces the observed geographic patterns of burnt area reasonably well, in particular the high incidence of fire in northern Australia and the more variable levels in the fuel-limited continental interior (Figure 2). The model overestimates the amount of fire in both southwestern and southeastern Australia, and underestimates the burnt area in northern Australia (Figure 2). Nevertheless, the model correctly predicts the broad-scale patterns in fire seasonality (Table 3), including the prevalence of fires in autumn and winter in northern Australia and in spring and summer in southern Australia. However, there are discrepancies in the timing of peak fire month and fire-season length in central Australia: the timing of the peak fire month can differ by more than 3 months and the fire season can be longer by a similar amount.
3.2 Continental response to future climate scenarios

The ensemble average climate shows a robust and significant increase in temperature over the 21st century (Figure 3) in response to both forcing scenarios. The response to the RCP4.5 scenario is less extreme: the RCP8.5 ensemble average increase in MAT is 4°C by the end of the 21st century, with changes of > 5°C in northwestern Australia, whereas the RCP4.5 ensemble response is 3°C although parts of northwestern Australia still have increases of >5°C (Figure 4). The average change in MAP is small in both scenarios. There is a small but robust and marginally significant decrease in precipitation in northern Australia of about 50 mm yr⁻¹ in the RCP4.5 scenario runs (Figure 4), although the decrease can be up to 200 mm yr⁻¹ in limited areas. Precipitation increases in some regions of the eastern coastal plains, southeastern Australia and Tasmania, and also southwestern Australia, but the changes are small, not robust and not significant. The decrease in precipitation in northern Australia is slightly smaller in the RCP8.5 simulations (ca 40 mm yr⁻¹), although again larger decreases (ca 125 mm yr⁻¹) occur in some places. Changes in MAP over the rest of the country are small, not consistent in sign, and not significant. These climate changes result in an increase in the frequency of “fire weather”, as measured by the cumulative values of the McArthur Mark 5 Forest Fire Danger Index (McArthur 1967; Noble et al. 1980) in forest and woodland biomes, and the Grassland Mark 3 Fire Danger Index (McArthur 1966; Pitman et al. 2007) in grasslands (Figure 2, Figure 3), and drive an overall increase in burnt area. Nevertheless, the modelled change in burnt area is only 0.05 Mkm² yr⁻¹ by the end of the century in the RCP4.5 simulations, and only 0.10 Mkm² yr⁻¹ in the RCP8.5 simulations, compared to 0.41 Mkm² yr⁻¹ in the historic simulation (Figure 3; Table 4). Thus, the simulated increase is only 12% (RCP4.5) or 24% (RCP8.5) of the historic burnt area. Part of the explanation for the decrease is that simulated surface wind speeds decrease during the fire season, limiting fire spread. The reduction in fire is accompanied by an increase in tree cover, from 19% during the historic period to 37% by the end of the 21st century in the RCP4.5 scenario and to 62% by the end of the 21st century in the RCP8.5 scenario. The increase
in tree cover leads to a shift in the ratio of fine to coarse fuel: although fuel loads are increased overall, the increase in coarse fuel is larger than the increase in fine fuel (Figure 5). As a result of this shift, the fuel dries more slowly and this inhibits fire. The increased tree cover reduces rates of fire spread (and hence burnt area) by further decreasing ground wind speed (Rothermel 1972). The increase in tree cover is due to the CO₂-induced increase in C₃ plant water-use efficiency (Figure 6). Comparison with the fixed-CO₂ simulation shows that climate change alone produces a decrease in tree cover by 10% and 8% in RCP4.5 and RCP8.5 respectively and no significant change in fire (Table 5).

The continental interior, occupied by shrubland and open savanna, is projected to experience a large increase in fire over the 21st century. Burnt area increases from 0.06 Mkm² yr⁻¹ in the historic simulations to 0.11 Mkm² yr⁻¹ (RCP 4.5) or 0.15 Mkm² yr⁻¹ (RCP8.5) by the end of the 21st century (Figure 5, Table 4), representing a 78% (RCP4.5) or 142% (RCP8.5) increase relative to the historic burnt area in this region. The increased temperatures and decreased precipitation over most of this region increase fire danger (Figure 4). Under present-day conditions, low fuel loads limit burnt area in much of the interior; increased temperature and decreased precipitation should further reduce vegetation productivity and hence fuel loads. Thus, the simulated increase in fire in the interior is predominantly a result of the direct impacts of CO₂ on vegetation productivity (Figure 6). In the fixed-CO₂ simulations, NPP is decreased by 13% in the RCP4.5 and 26% in the RCP8.5 simulations compared to the historic simulation, resulting in reduced fuel and a decrease in burnt area compared to the historic period in both scenarios (Table 5; Figure 6).

Southeastern Australia has some of the largest increases in fire, with some areas experiencing a 10-20% increase in burnt area by the end of the century in both RCP simulations (Figure 4, Table 4). These increases result from a combination of increased fuel load and decreased fuel moisture (Figure 5). The increase in fuel load is a result of CO₂ fertilisation (Figure 6): in the fixed-CO₂ simulations fuel load is reduced to 1.06 and 0.73 kg m⁻², in the RCP4.5 and RCP8.5 simulations respectively, compared to 1.2 kg m⁻² in the control simulation. Despite the increase in fire, tree cover still increases in the southeastern interior (Figure 4). In contrast, tree cover is reduced in forested coastal regions (from 81% in the control simulation to 73-74% in the RCP simulations, Table 4), largely due to increases in fire in areas with low fire in the historic period (Figure 4).

Southwestern Australia is characterized by large projected increases in fire over the 21st century (Figure 4). Burnt area increases from 0.038 Mkm² yr⁻¹ in the historic simulations to 0.052 Mkm² yr⁻¹ (RCP4.5) and 0.049 Mkm² yr⁻¹ (RCP8.5) (Figure 5, Table 4), representing a 37% (RCP4.5) or 28%...
(RCP8.5) increase in the historic burnt area. There is only a small and non-robust change in fuel moisture, and the increase in fire is almost entirely driven by an increase in fuel loads (Figure 5) with average fuel loads increasing from 0.27 kg m\(^{-2}\) to 0.33 and 0.36 kg m\(^{-2}\) in RCP4.5 and RCP 8.5 respectively. This increase in fuel load is a result of CO\(_2\) fertilization. In the fixed-CO\(_2\) simulations, fuel loads decreased by 0.02 kg m\(^{-2}\) in the RCP4.5 and 0.08 kg m\(^{-2}\) in the RCP8.5 simulations compared to the historic simulation (Table 5). The regional increase in fire is driven by changes in the woodland and grassland areas of the interior; fire decreases in those areas where forest replaces sclerophyll woodland (Figure 4; Figure 7) due a higher proportion of coarser fuel which dries more slowly. Overall, tree cover in southwestern Australia increases from 17% in the historic simulations to 22% in the RCP4.5 and 32% in the RCP8.5 simulations, partly due to the conversion from sclerophyll woodland to forest but also due to increases in the interior despite the increase in fire.

3.4. Impacts of changing fire regimes and climate on vegetation patterns

The simulated changes in fire regimes and climate produce noticeable changes in vegetation distribution by the end of the 21\(^{st}\) century (Figure 7). The pattern of expansion/contraction of major biomes is similar in the two RCP scenarios, but more exaggerated in RCP8.5. The area of grass and shrubland is reduced from 5.34 Mkm\(^{2}\) in the historic simulation to 4.91 Mkm\(^{2}\) in the RCP4.5 and 3.08 Mkm\(^{2}\) in the RCP8.5 simulation, equivalent to a decrease of 8% and 42% respectively. These changes largely reflect the expansion of tropical savanna in northern Australia (Figure 7). This conversion occurs because of CO\(_2\) fertilization and despite small but significant increases in fire: there is no southward expansion of tropical savanna in the fixed-CO\(_2\) RCP4.5 simulations and grasslands expand in the fixed-CO\(_2\) RCP8.5 simulations (except in the region along the northeastern coast). Much larger increases in fire (by ca 15\%) cause grassland to expand into sclerophyll woodlands in southern Australia (Figure 7), reducing the area of sclerophyll woodlands by 0.32 Mkm\(^{2}\) in RCP4.5 and 0.25 Mkm\(^{2}\) in RCP8.5. This expansion is even more pronounced in the fixed-CO\(_2\) experiments: in the RCP8.5 simulation, for example, sclerophyll woodland is barely expanded beyond the area occupied by temperate forests in the present day. Thus, increased CO\(_2\) offsets the negative impacts of increased fire on sclerophyll woodlands in southern Australia. The area of warm temperate broadleaved forest expands during the 21\(^{st}\) century by 45\% and 104\% respectively in the RCP4.5 and RCP8.5 simulations. This expansion also reflects CO\(_2\) fertilization as the area of warm temperate broadleaved forest is reduced slightly compared to present in the fixed-CO\(_2\) simulations (Figure 7).
Even within regions where there is no change in biome by the end of the 21\textsuperscript{st} century, the simulated changes in climate and fire regimes result in changes in the character of the vegetation (Figure 8). Thus, areas that are characterized as tropical savanna both today and at the end of the 21\textsuperscript{st} century nevertheless show an increase in tree cover. The increase in tree cover results from a large increase in the abundance of non-resprouting trees and there is a decrease in the relative importance of resprouters in these ecosystems (Figure 8). Both the increase in tree cover and the increase in the relative importance of non-resprouters are consistent with the simulated decrease in fire. In areas where tropical forests persist, increased fire leads to a decrease in tree cover overall but an increase in the abundance of resprouting trees which partially offsets the decrease in non-resprouting trees (Figure 8). Again, both the decrease in tree cover and the shift in the balance of resprouting to non-resprouting trees are consistent with the change in fire. Areas that persist as sclerophyll woodland in southeastern and southwestern Australia show an increase in tree cover despite the simulated increase in fire, and this is reflected in an increase in the importance of resprouting trees. Areas that persist as grass and shrubland, nevertheless show a small CO\textsubscript{2}-induced increase in woody cover. The increase in non-resprouting trees is greater than the increase in resprouting trees, because they have a competitive advantage over resprouters in terms of regeneration from seed in areas of low vegetation density. The incidence of fire increases but is still limited by fuel availability, and thus is not a major determinant in the balance between resprouters and non-resprouters in this ecosystem. The balance between resprouting and non-resprouting trees is affected by changes in fire regimes but is also affected by changes in other ecosystem properties. This is most clearly seen in areas that persist as temperate forests in southeastern Australia. The decrease in tree cover in this region (Figure 8) is largely driven by increased aridity, rather than fire. In the absence of a significant increase in fire, the relative abundance of non-resprouters increases because they have higher regeneration rates than non-resprouters. However, the expected impact of a change in fire regime on the relative abundance of resprouters and non-resprouters is seen in the comparison of the RCP4.5 and RCP8.5 results, where the larger increase in fire in the RCP8.5 scenario results in a smaller relative increase in non-resprouters and a smaller relative decrease in resprouters (Figure 8).

\textbf{Discussion}

Previous studies have suggested that the risk of fire, as measured by some form of fire danger index, is likely to increase across Australia in response to projected future changes in temperature and precipitation (Williams \textit{et al.} 2001; Hennessy \textit{et al.} 2005; Lucas \textit{et al.} 2007; Pitman \textit{et al.} 2007; Fox-Hughes \textit{et al.} 2014). There is a robust increase in fire danger at the end of the 21\textsuperscript{st} century in the RCP8.5 scenario over almost the entire continent (Figure 4). The extent of the region...
characterized by increased fire danger by the end of the 21st century is more limited in the RCP4.5 simulations but nevertheless most of western and central Australia shows an increase in fire danger. However, increased fire danger does not map on to changes in burnt area. Our simulations show reduced burnt area in northern Australia despite a significant and robust increase in fire danger. This reflects the fact that changes in vegetation density and in the nature of the available fuel can significantly affect the spread of fire. Similarly, the areas of southern Australia that show the largest increases in fire danger are not the areas which show the largest changes in burnt area. In the RCP4.5 scenario runs, regions in southeastern Australia that show reduced fire danger actually show an increase in burnt area. Again, the increase in burnt area in this region reflects the role of vegetation changes – in particular the increase in fuel loads – in modulating fire regimes. Fire danger indices were developed as a management tool to predict the likelihood of fire in response to changes in fire-promoting weather conditions (McArthur 1973; Deeming et al. 1977; Van Wagner 1987; Matthews 2009). They are not appropriate tools to examine the consequences of long-term changes in climate, changes that impact vegetation properties directly, on fire regimes.

The direct effects of increasing CO$_2$ on vegetation productivity and water-use efficiency influence simulated fire regimes. CO$_2$ effects tend to increase fuel loads and fuel continuity in arid regions where fuel-limitation rather than climate conditions currently limits the occurrence of fire. However, in more wooded regions, CO$_2$ leads to increased vegetation density and this generally reduces burnt area. The role of increasing CO$_2$ on vegetation productivity and fuel loads has been highlighted as the dominant cause of changing fire regimes on glacial-interglacial times scales (Martin Calvo et al. 2014). Increased productivity and fuel loads, and increased vegetation density, has also been identified as a response to CO$_2$ fertilisation in simulations of 21st century changes in fire regimes and emissions made with LPJ-GUESS-SIMFIRE (Knorr et al. 2016b), although the impact on burnt area was not quantified. The projections of future fire regimes used in the recent IPCC report (Settele et al. 2014) were based on statistical modelling from Moritz et al. (2012), which cannot account for the independent effects of changes in CO$_2$ on fuel loads. Fire-enabled DGVMs, which explicitly simulate the impact of CO$_2$ on fuel loads, are more appropriate tools to examine the consequences of long-term changes in climate on fire regimes.

According to our simulations, the overall increase in burnt area over the course of the 21st century is comparatively small with only an additional 1% of the continent burnt each year compared to today. There are, however, shifts in the spatial patterns of burning with increased fire in woodland regions in the south and decreased fire in the north, and these shifts are likely to have important consequences on the economic impacts of fire (Ashe et al. 2008; Compton and McAneney 2008;
Nevertheless, although the changes in fire are muted, the combined effects of changing climate, atmospheric CO\textsubscript{2} concentration and fire regimes have large impacts on ecosystems. According to our simulations, 22% of the continent will be affected by changes large enough to cause a shift in biome type under the RCP4.5 scenario, while 49% of the continent will be affected by biome shifts in the RCP8.5 scenario. The area of tropical forests increases by ca 218% (648%) and the area of tropical savannas by ca 45% (200%) by the end of the century in the RCP 4.5 (RCP8.5) scenario. At the same time, the area of sclerophyll woodlands decreases by ca 13% (23%) and the area of grass and shrublands by ca 9% (43%) by the end of the century in the RCP 4.5 (RCP8.5) scenario. Even in regions where the combined influence of climate, CO\textsubscript{2} and fire is insufficient to cause biome changes, there are changes in the relative abundance of different PFTs. Although we have focused on changes in tree cover and in the abundance of resprouting trees, because of the potential feedbacks between these vegetation parameters and fire, the simulations also show large shifts in the abundance of evergreen versus deciduous trees or between broadleaf and needleleaf trees in specific regions. These changes in ecosystem properties could have significant impacts on biodiversity and ecosystem services (Steffen et al. 2009; Booth 2012).

Human-set fires are a major component of modern-day fire regimes in many regions of the world and may affect both the type and timing of fires (Archibald et al., 2013). Human-set fires are a major management tool in northern Australia, for example, and have been invoked to explain the large area burnt there annually (Murphy et al., 2013). However, in contrast to many other fire models, LPX-Mv1 does not include anthropogenic ignitions. Our motivation for this is that the number of ignitions is not a limiting factor on overall burnt area at a regional scale; regional analyses have shown that burnt area is strongly controlled by fuel availability and fuel moisture (Bistinas et al., 2014; Knorr et al., 2016a). Indeed, the apparent relationship between population density and burnt area (which forms the basis for the parameterisation of human ignitions in other fire models: Hantsen et al., 2016) is an artifact due to the causal correlations between population density, vegetation productivity and aridity (Bistinas et al., 2014). Lack of anthropogenic ignitions does not explain the underestimation of burnt area in northern Australia in our simulations, which is a result of simulated fuel loads being too wet throughout the year and is not improved by increasing or changing the timing of ignitions.

The RCP4.5 and RCP8.5 scenarios represent a moderate and a high-end increase in radiative forcing over the 21\textsuperscript{st} century, leading to an increase in global temperature of 1.8±0.7 and 3.7±1.1\degree C respectively by the end of the century. However, our simulations do not take into account possible
increases in the frequency of lightning associated with warming temperatures and increased convection because of the large uncertainty about the quantitative relationship between these variables. Increases in the number of lightning strikes might lead to increases in ignitions, but this would not necessarily translate into an increase in fire – there is an increasing amount of evidence indicating that the number of ignitions is not the limiting factor on biomass burning globally (Bistinas et al. 2014; Knorr et al. 2016). Nevertheless, changes in lightning ignitions could be important at a regional scale and it would be useful to take such changes into account. Our results involve a further simplification in that we do not include anthropogenic fire suppression, or how this might change in response to the growth of population or changing patterns of human settlement. Although this decision was largely pragmatic, it also reflects the relatively simple approach to treating fire suppression in state-of-the-art models (Hantson et al. 2016).

The trajectory of future climate and CO₂ change is uncertain and our focus on the RCP4.5 and RCP8.5 scenarios therefore arbitrary. Furthermore, there are non-negligible differences in the response of different climate models to these changes and the use of an ensemble of models does not guarantee that the average state is realistic (Tebaldi and Knutti 2007; Knutti 2010). Furthermore, LPX-Mv1 itself has regional biases in both the amount of vegetation cover (and hence fuel loads) and in the simulated burnt area under modern conditions. These biases likely affect the absolute magnitude of simulated changes during the 21st century, although they should not impact on the direction and relative magnitudes of change. Thus, for many reasons, our results are indicative rather than definitive statements about the likely changes in regional fire regimes and vegetation during the 21st century across Australia. However, process-based modelling provides a tool for addressing the complexity of the interaction between vegetation and fire, and these simulations show that future fire regimes are influenced by these interactions. The projections should provide a more robust basis for developing fire management and mitigation strategies.

Conclusion

Simulations with the LPX-Mv1 DGVM show an increase in burnt area of between 12-24% by the end of the 21st century under the RCP4.5 and RCP8.5 scenarios. The change in burnt area is modest given the simulated changes in climate and the large increases in climate-determined “fire risk” as measured by the McArthur Fire Danger Index. CO₂-induced changes in vegetation productivity modulate the direct climate impacts on fire regimes, leading to increased burnt area in currently fuel-limited regions but decreasing burnt area in many forested regions. Changes in fire regimes in turn affect natural ecosystems, leading to changes in the relative abundance of types of plant (grass versus trees, resprouters versus non-resprouters) within ecosystems and substantial shifts in the
distribution of major vegetation types. Process-based modelling makes it possible to account for the complex two-way interactions between fire and vegetation and thus to make projections of the response of both to future climate changes. There are uncertainties associated with future climate projections, and in the modelling of vegetation and fire responses to climate change. Nevertheless, the simulations presented here offer a firmer foundation for understanding future climate impacts on fire and vegetation than approaches based on extrapolation from modern climate-fire relationships.

Acknowledgements

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and the climate modelling groups for producing and making available their model output. (For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.) The analyses and figures are based on data archived by 18 June 2013. DIK was supported by an iMQRES at Macquarie University and postdoctoral funding from the University of Reading. We thank Colin Prentice for comments on the draft manuscript.

References


Geng S, Auburn JS, Brandstetter E, Li B (1988) A program to simulate meteorological variables: Documentation for SIMMETEO. Agronomy Progress Report 204, Department of Agronomy and Range Science, University of California, Davis CA.


Report of the Intergovernmental Panel on Climate Change’ (Eds TF Stocker D Qin, G-K Plattner, M Tignor, SK Allen, J Doschung, A Nauels, Y Xia, V Bex, PM Midgley), pp. 953-1028. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA)


McArthur AG (1966) ‘Weather and grassland fire behaviour’ (Forestry and Timber Bureau, Department of National Development, Commonwealth of Australia)

McArthur AG (1967) ‘Fire behaviour in eucalypt forests’ (Forestry and Timber Bureau, Canberra).


Murphy BP, Bradstock RA, Boer MM, Carter J, Cary GJ, Cochrane MA, Fensham RJ, Russell-

Noble IR, Bary GAA, Gill AM (1980), McArthur's fire danger meters expressed as equations,

Pitman AJ, Narisma GT, McAneney J (2007) The impact of climate change on the risk of forest and
grassland fires in Australia *Climate Change* **84**, 383-401.

Prentice IC, Kelley DI, Foster PN, Friedlingstein P, Harrison SP, Bartlein PJ (2011) Modelling fire

Price C, Rind D (1994) Possible implications of global climate change on global lightning

Romps DM, Seeley, JT, Vollaro D, Molinari J (2014) Projected increase in lightning strikes in the

Rothermel RC (1972) A Mathematical Model for Predicting Fire Spread in Wildland Fuels. US
Forestry Service.

Available online from the Carbon Dioxide Information Analysis Center [http://cdiac.ornl.gov],
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Russell-Smith J, Yates CP, Whitehead PJ, Smith R, Craig R, GE Allan, Thackway R, Frakes I,
Cridland S, Meyer MCP, Gill AM (2007) Bushfires' down under: patterns and implications of

Terrestrial and inland water systems. In: ‘Climate Change 2014: Impacts, Adaptation, and
Vulnerability. Part A: Global and Sectoral Aspects’. (Eds Field CB, Barros VR, Dokken DJ,
Mach KJ, Mastrandrea MA, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B,
Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL), pp. 271-359. (Cambridge
University Press, Cambridge, United Kingdom and New York, NY, USA).

and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change

Steffen W, Burbidge AA, Hughes L, Kitching R, Lindenmayer D, Musgrave W, Stafford Smith M,
Werner PA (2009) Australia’s Biodiversity and Climate Change: A Strategic Assessment of the
Vulnerability of Australia’s Biodiversity to Climate Change. (CSIRO Publishing, Canberra)


Figure and Table Captions

Figure 1. Description of the structure of the fire component of LPX-Mv1. Climate and lightning inputs to the model are identified by white boxes, outputs from the vegetation dynamics component of the model are identified by green boxes. The internal processes and exchanges that are explicitly simulated by the fire component of the model are colour-coded, where pale green boxes show state variables associated with fuel load, blue boxes show state variable associated with fuel moisture, yellow boxes show state variables associated with ignitions, red boxes show state variables associated with fire regime, and brown boxes show state variables associated with mortality and biomass consumption.

Figure 2. Comparison of observed (left-hand column) and simulated (right-hand column) vegetation and fire during the recent period. Observed values of (a) tree cover were obtained from DeFries and Hansen (2009). Observed values for (b) carbon were obtained from Ruesch and Gibbs (2008). Observed (c) average burnt area for the period 1997 to 2006 is from GFED4 (Giglio et al 2013). Grid cells with >50% cropland and/or urban land are shaded in grey; these cells are not taken into account in the model benchmarking.

Figure 3. Changes in climate, fire risk, vegetation, fuel load and burnt area over Australia through the 21st century in simulations driven by the RCP4.5 and RCP8.5 scenarios. The time series (bold lines) are ensemble averages of the model results, smoothed using a 10-year moving window, where the RCP4.5 simulations are in blue and the RCP8.5 simulations are in red, for (a) mean annual temperature (MAT, °C), (b) mean annual precipitation (MAP, mm/yr), (c) the ratio of actual to equilibrium evapotranspiration (α, unitless), (d) fire risk as measured by the McArthur cumulative fire danger index (FDI), (e) tree cover (%), (f) total fuel load (kg/m²) and burnt area (%). The range in the individual model simulations is indicated by the shaded bands (red for RCP4.5, blue for RCP8.5). The dashed horizontal lines indicate the average value of each variable during the last decade of the historic simulation.

Figure 4. Maps of the ensemble changes in climate, fire risk, vegetation and fire from the last decade of the 21st century (2090-2099) for the RCP4.5 and RCP8.5 experiments compared to the historic period (1997-2006). The climate variables are mean annual temperature (MAT, °C), mean annual precipitation (MAP, mm/yr) and the ratio of actual to potential evapotranspiration (α). Fire danger is represented by the McArthur cumulative fire danger index (FDI). The vegetation parameters are tree cover (%) and fuel load (kg/m²), while fire is represented by burnt area (%). Colours show the absolute change and stippling shows the robustness of the signal (as measured by...
the standard deviation (sd) of the model results divided by the ensemble mean for each grid cell), where stippled areas indicate higher confidence in the signal.

Figure 5. Factors affecting regional changes in burnt area in northern (N), central (C), southwestern (SW) and southeastern (SE) Australia. The histograms show the mean change in burnt area (%), tree cover (%), minimum fuel moisture (i.e. the mean fuel moisture during the month with the lowest overall values of fuel moisture, %), coarse fuel (kg/m²) and fine fuel (kg/m²) in the last decade of the 21st century (2090-2099) for the RCP4.5 and RCP8.5 experiments compared to the historic period (1997-2006). The black bars show the standard deviation of the individual experiments.

Figure 6. Maps of the difference in burnt area (%), net primary production (NPP, kg C/m²) and tree cover (%) in the last decade of the 21st century (2090-2099) between the RCP simulations with fixed CO₂ and the simulations in which both climate and CO₂ were allowed to vary. Positive values therefore have the sense here of the impact of CO₂ fertilisation on the variable.

Figure 7. Maps of the ensemble changes in vegetation distribution during the last decade of the 21st century (2090-2099) for the RCP4.5 and RCP8.5 experiments compared to the historic period (1997-2006). To isolate the impact of CO₂ fertilisation on the vegetation, the results for the same decade of the RCP4.5 and RCP8.5 fixed-CO₂ experiments are also shown. The simulated abundance of individual plant functional types (PFTs) was converted to major vegetation types (biomes) using a modified version of the algorithm described in Prentice et al. (2011). The change in the area of each biome (Mkm²) between the last decade of the historic period and the last decade of the 21st century is shown in the box-and-whisker plots, where the black lines shows the median value, the box shows the interquartile range and the whiskers show the 95% range of the model values.

Figure 8. Impact of changes in climate, CO₂ and fire on plant functional types (PFTs) in regions where biomes remain unchanged by the end of the 21st century in the RCP4.5 and 8.5 scenario simulations. The plots show the change in the abundance of resprouting and non-resprouting trees (%) compared with changes in burnt area (%) and tree cover (%) within each of the five major biomes, grass and shrubland, tropical savanna, tropical forest, sclerophyll woodland and temperate forest.

Table 1: Summary of the simulation protocol for model spin-up and the simulations.
Table 2: Information on the models used to provide future climate scenarios. OA models are coupled ocean-atmosphere models; OAC models include a marine and terrestrial carbon cycle. The resolution (number of grid cells by latitude and longitude) is that of the atmospheric and land-surface components of each model.

Table 3: Benchmarking metrics for the modern simulation of Australian vegetation and fire. The Manhattan Metric (MM) is used to assess vegetation properties, the normalized mean error (NME) to assess fine fuel loads, burnt area and carbon, and the mean phase difference (MPD) to assess fire seasonality. Values for the mean and random null model for each variable are given for comparison. Values that are better than the mean null model are shown in italics, values that are better than the random null model are indicated by an asterisk.

Table 4: Summary of changes in climate (mean annual temperature: MAT; mean annual precipitation: MAP, ratio of actual to equilibrium evapotranspiration: $\alpha$), vegetation parameters (net primary production: NPP; tree cover, amount of fine fuel, amount of coarse fuel) and fire (burnt area) over the 21st century, based on ensemble averages of the simulations driven by the RCP4.5 and RCP8.5 climate scenarios, for Australia as a whole and for the four sub-regions used in this study. The total land area for each region is given in brackets, for comparison with the values for burnt area.

Table 5: Summary of changes in vegetation parameters (net primary production: NPP; tree cover, amount of fine fuel, amount of coarse fuel) and fire (burnt area) over the 21st century, based on ensemble averages of the simulations driven by the RCP4.5 and RCP8.5 climate scenarios but with CO$_2$ held constant at the 2006 level of 380.8 ppm (fixed-CO$_2$ experiment).
Table 1: Summary of the simulation protocol for model spin-up and the simulations.

<table>
<thead>
<tr>
<th>Time period</th>
<th>CO₂</th>
<th>Maximum &amp; minimum temperature, precipitation, rain days, and sunshine hours</th>
<th>Wind speed</th>
<th>Lightning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin-up</td>
<td>286 ppm</td>
<td>detrended CRU TS3.1</td>
<td>detrended NCEP</td>
<td>climatology LIS-OTD</td>
</tr>
<tr>
<td>1850-1900</td>
<td>transient</td>
<td>detrended CRU TS3.1</td>
<td>detrended NCEP</td>
<td>climatology LIS-OTD</td>
</tr>
<tr>
<td>1901-1947</td>
<td>transient</td>
<td>transient CRU TS3.1</td>
<td>detrended NCEP</td>
<td>climatology LIS-OTD</td>
</tr>
<tr>
<td>1948-1979</td>
<td>transient</td>
<td>transient CRU TS3.1</td>
<td>transient NCEP</td>
<td>climatology LIS-OTD</td>
</tr>
<tr>
<td>1980-2006</td>
<td>transient</td>
<td>transient CRU TS3.1</td>
<td>transient NCEP</td>
<td>climatology LIS-OTD</td>
</tr>
<tr>
<td>2006-2100</td>
<td>transient</td>
<td>Transient</td>
<td>transient</td>
<td>climatology LIS-OTD</td>
</tr>
</tbody>
</table>
Table 2: Information on the models used to provide future climate scenarios. OA models are coupled ocean-atmosphere models; OAC models include a marine and terrestrial carbon cycle. The resolution (number of grid cells by latitude and longitude) is that of the atmospheric and land-surface components of each model.

<table>
<thead>
<tr>
<th>Code</th>
<th>Centre</th>
<th>Type</th>
<th>Original resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNRM-CM5</td>
<td>Centre National de Recherches Meteorologique</td>
<td>OA</td>
<td>128, 256</td>
</tr>
<tr>
<td>GISS-CM5</td>
<td>NASA Goddard Institute for Space Studies</td>
<td>OA</td>
<td>90, 144</td>
</tr>
<tr>
<td>HadGEM2-CC</td>
<td>Hadley Centre, UK Meteorological Office</td>
<td>OA</td>
<td>145, 192</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>Meteorological Research Institute</td>
<td>OA</td>
<td>160, 320</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>Hadley Centre, UK Meteorological Office</td>
<td>OAC</td>
<td>145, 192</td>
</tr>
<tr>
<td>IPSL-CM5a-LR</td>
<td>Institut Pierre-Simon Laplace</td>
<td>OAC</td>
<td>96, 96</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>Japan Agency for Marine-Earth Science and Technology</td>
<td>OAC</td>
<td>64, 128</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>Max Planck Institute for Meteorology</td>
<td>OAC</td>
<td>96, 192</td>
</tr>
<tr>
<td>BCC-CSM1-1</td>
<td>Beijing Climate Center</td>
<td>OAC</td>
<td>64, 128</td>
</tr>
</tbody>
</table>
Table 3: Benchmarking metrics for the modern simulation of Australian vegetation and fire. The Manhattan Metric (MM) is used to assess vegetation properties, the normalized mean error (NME) to assess fine fuel loads, burnt area and carbon, and the mean phase difference (MPD) to assess fire seasonality. Values for the mean and random null model for each variable are given for comparison. Values that are better than the mean null model are shown in italics, values that are better than the random null model are indicated by an asterisk.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Tree cover</th>
<th>Grass cover</th>
<th>Fine fuel</th>
<th>Burnt area</th>
<th>Fire season</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed mean</td>
<td>8.4%</td>
<td>65%</td>
<td>230 g/m²</td>
<td>6.8%</td>
<td>n/a</td>
<td>2388 gC m²</td>
</tr>
<tr>
<td>Simulated mean</td>
<td>4.9%</td>
<td>55%</td>
<td>202 g/m²</td>
<td>5.0%</td>
<td>n/a</td>
<td>3481 gC m²</td>
</tr>
<tr>
<td>Mean null model</td>
<td>0.43</td>
<td>0.49</td>
<td>1</td>
<td>1</td>
<td>0.45</td>
<td>1</td>
</tr>
<tr>
<td>Random null model</td>
<td>0.52±0.002</td>
<td>0.66±10.002</td>
<td>1.44±0.21</td>
<td>1.14±0.003</td>
<td>0.47±0.002</td>
<td>1.19±0.013</td>
</tr>
<tr>
<td>LPX-Mv1 mean</td>
<td>0.16*</td>
<td>0.51*</td>
<td>0.73*</td>
<td>0.88*</td>
<td>0.43*</td>
<td>0.94*</td>
</tr>
</tbody>
</table>
Table 4: Summary of changes in climate (mean annual temperature: MAT; mean annual precipitation: MAP, ratio of actual to equilibrium evapotranspiration: $\alpha$), vegetation parameters (net primary production: NPP; tree cover, amount of fine fuel, amount of coarse fuel) and fire (burnt area) over the 21st century, based on ensemble averages of the simulations driven by the RCP4.5 and RCP8.5 climate scenarios, for Australia as a whole and for the four sub-regions used in this study. The total land area for each region is given in brackets, for comparison with the values for burnt area.

<table>
<thead>
<tr>
<th></th>
<th>MAT (°C)</th>
<th>MAP (mm/yr)</th>
<th>$\alpha$</th>
<th>NPP (kg C/m² yr)</th>
<th>Tree Cover (%)</th>
<th>Fine Fuel (kg /m²)</th>
<th>Coarse Fuel (kg /m²)</th>
<th>Burnt Area (M km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Australia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>21</td>
<td>503</td>
<td>0.20</td>
<td>0.29</td>
<td>9.81</td>
<td>0.16</td>
<td>0.80</td>
<td>0.41</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>24 ± 0.56</td>
<td>494 ± 28</td>
<td>0.19 ± 0.02</td>
<td>0.35 ± 0.03</td>
<td>14 ± 1.57</td>
<td>0.22 ± 0.02</td>
<td>1.50 ± 0.13</td>
<td>0.46 ± 5.96</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>25 ± 0.92</td>
<td>487 ± 48</td>
<td>0.18 ± 0.02</td>
<td>0.56 ± 0.07</td>
<td>22 ± 4.25</td>
<td>0.28 ± 0.05</td>
<td>2.10 ± 0.26</td>
<td>0.51 ± 11</td>
</tr>
<tr>
<td><strong>South East</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>12</td>
<td>832</td>
<td>0.58</td>
<td>0.78</td>
<td>81</td>
<td>1.20</td>
<td>12.1</td>
<td>0.005</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>14 ± 0.33</td>
<td>786 ± 39</td>
<td>0.56 ± 0.02</td>
<td>0.97 ± 0.03</td>
<td>73 ± 2.59</td>
<td>1.46 ± 0.26</td>
<td>18.1 ± 6.00</td>
<td>0.007 ± 0.11</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>16 ± 0.74</td>
<td>807 ± 75</td>
<td>0.48 ± 0.03</td>
<td>1.19 ± 0.06</td>
<td>74 ± 3.83</td>
<td>1.68 ± 0.32</td>
<td>22.5 ± 6.2</td>
<td>0.01 ± 0.31</td>
</tr>
<tr>
<td><strong>South West</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>17</td>
<td>421</td>
<td>0.26</td>
<td>0.37</td>
<td>17</td>
<td>0.27</td>
<td>0.28</td>
<td>0.037</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>20 ± 0.48</td>
<td>394 ± 47</td>
<td>0.23 ± 0.02</td>
<td>0.44 ± 0.04</td>
<td>22 ± 3.18</td>
<td>0.33 ± 0.04</td>
<td>0.47 ± 0.17</td>
<td>0.052 ± 0.38</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>22 ± 0.88</td>
<td>351 ± 58</td>
<td>0.19 ± 0.03</td>
<td>0.51 ± 0.10</td>
<td>32 ± 3.84</td>
<td>0.36 ± 0.09</td>
<td>0.80 ± 0.20</td>
<td>0.049 ± 0.84</td>
</tr>
<tr>
<td><strong>Central</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>20</td>
<td>251</td>
<td>0.11</td>
<td>0.14</td>
<td>0.81</td>
<td>0.02</td>
<td>0.006</td>
<td>0.06</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>23 ± 0.54</td>
<td>232 ± 31</td>
<td>0.10 ± 0.01</td>
<td>0.17 ± 0.03</td>
<td>0.63 ± 0.14</td>
<td>0.05 ± 0.01</td>
<td>0.002 ± 0.001</td>
<td>0.11 ± 2.98</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>25 ± 0.88</td>
<td>210 ± 50</td>
<td>0.08 ± 0.02</td>
<td>0.22 ± 0.06</td>
<td>2.62 ± 1.18</td>
<td>0.06 ± 0.02</td>
<td>0.003 ± 0.001</td>
<td>0.15 ± 4.49</td>
</tr>
<tr>
<td><strong>North</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>27</td>
<td>1161</td>
<td>0.31</td>
<td>0.50</td>
<td>16</td>
<td>0.22</td>
<td>0.40</td>
<td>0.08</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>29 ± 0.57</td>
<td>1113 ± 82</td>
<td>0.33 ± 0.03</td>
<td>0.65 ± 0.08</td>
<td>37 ± 9.52</td>
<td>0.36 ± 0.10</td>
<td>2.90 ± 1.7</td>
<td>0.05 ± 0.88</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>31 ± 1.05</td>
<td>1121 ± 139</td>
<td>0.32 ± 0.04</td>
<td>0.87 ± 0.13</td>
<td>62 ± 13</td>
<td>0.54 ± 0.19</td>
<td>5.3 ± 3.0</td>
<td>0.04 ± 0.62</td>
</tr>
</tbody>
</table>
Table 5: Summary of changes in vegetation parameters (net primary production: NPP; tree cover, amount of fine fuel, amount of coarse fuel) and fire (burnt area) over the 21st century, based on ensemble averages of the simulations driven by the RCP4.5 and RCP8.5 climate scenarios but with CO₂ held constant at the 2006 level of 380.8 ppm (fixed-CO₂ experiment).

<table>
<thead>
<tr>
<th>Region</th>
<th>NPP (kg C/m² yr)</th>
<th>Tree Cover (%)</th>
<th>Fine Fuel (kg/m²)</th>
<th>Coarse Fuel (kg/m²)</th>
<th>Burnt Area (M km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Australia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>0.29</td>
<td>9.81</td>
<td>0.16</td>
<td>0.80</td>
<td>0.41</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>0.26 ± 0.03</td>
<td>8.28 ± 0.62</td>
<td>0.14 ± 0.01</td>
<td>0.80 ± 0.11</td>
<td>0.36 ± 4.89</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>0.23 ± 0.03</td>
<td>6.31 ± 1.12</td>
<td>0.10 ± 0.01</td>
<td>0.48 ± 0.07</td>
<td>0.28 ± 6.80</td>
</tr>
<tr>
<td><strong>South East</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>0.78</td>
<td>81</td>
<td>1.20</td>
<td>12.1</td>
<td>0.005</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>0.83 ± 0.03</td>
<td>69 ± 1.98</td>
<td>1.06 ± 0.16</td>
<td>10.7 ± 3.20</td>
<td>0.004 ± 0.09</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>0.81 ± 0.04</td>
<td>56 ± 6.59</td>
<td>0.73 ± 0.06</td>
<td>0.58 ± 5.90</td>
<td>0.006 ± 0.27</td>
</tr>
<tr>
<td><strong>South West</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>0.37</td>
<td>17</td>
<td>0.27</td>
<td>0.28</td>
<td>0.04</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>0.35 ± 0.04</td>
<td>13 ± 2.09</td>
<td>0.25 ± 0.03</td>
<td>0.36 ± 0.06</td>
<td>0.04 ± 0.50</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>0.28 ± 0.05</td>
<td>8.02 ± 2.19</td>
<td>0.19 ± 0.04</td>
<td>0.35 ± 0.05</td>
<td>0.03 ± 0.92</td>
</tr>
<tr>
<td><strong>Central</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>0.14</td>
<td>0.81</td>
<td>0.02</td>
<td>0.006</td>
<td>0.06</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>0.12 ± 0.02</td>
<td>0.21 ± 0.06</td>
<td>0.02 ± 0.01</td>
<td>0.003 ± 0.001</td>
<td>0.06 ± 1.91</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>0.10 ± 0.02</td>
<td>0.08 ± 0.04</td>
<td>0.01 ± 0.01</td>
<td>0.002 ± 0.001</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>North</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Historic</td>
<td>0.50</td>
<td>16</td>
<td>0.22</td>
<td>0.40</td>
<td>0.08</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>0.43 ± 0.06</td>
<td>16 ± 3.53</td>
<td>0.15 ± 0.05</td>
<td>0.93 ± 3.90</td>
<td>0.08 ± 0.61</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>0.37 ± 0.09</td>
<td>14 ± 5.73</td>
<td>0.10 ± 0.05</td>
<td>0.58 ± 0.33</td>
<td>0.07 ± 0.78</td>
</tr>
</tbody>
</table>
Figure 1. Description of the structure of the fire component of LPX-Mv1. Climate and lightning inputs to the model are identified by white boxes, outputs from the vegetation dynamics component of the model are identified by green boxes. The internal processes and exchanges that are explicitly simulated by the fire component of the model are colour-coded, where pale green boxes show state variables associated with fuel load, blue boxes show state variable associated with fuel moisture, yellow boxes show state variables associated with ignitions, red boxes show state variables associated with fire regime, and brown boxes show state variables associated with mortality and biomass consumption.
Figure 2. Comparison of observed (left-hand column) and simulated (right-hand column) vegetation and fire during the recent period. Observed values of (a) tree cover were obtained from DeFries and Hansen (2009). Observed values for (b) carbon were obtained from Ruesch and Gibbs (2008). Observed (c) average burnt area for the period 1997 to 2006 is from GFED4 (Giglio et al 2013). Grid cells with >50% cropland and/or urban land are shaded in grey; these cells are not taken into account in the model benchmarking.
Figure 3. Changes in climate, fire risk, vegetation, fuel load and burnt area over Australia through the 21st century in simulations driven by the RCP4.5 and RCP8.5 scenarios. The time series (bold lines) are ensemble averages of the model results, smoothed using a 10-year moving window, where the RCP4.5 simulations are in blue and the RCP8.5 simulations are in red, for (a) mean annual temperature (MAT, °C), (b) mean annual precipitation (MAP, mm/yr), (c) the ratio of actual to equilibrium evapotranspiration (α, unitless), (d) fire risk as measured by the McArthur cumulative fire danger index (FDI), (e) tree cover (%), (f) total fuel load (kg/m²) and burnt area (%). The range in the individual model simulations is indicated by the shaded bands (red for RCP4.5, blue for RCP8.5). The dashed horizontal lines indicate the average value of each variable during the last decade of the historic simulation.
Figure 4. Maps of the ensemble changes in climate, fire risk, vegetation and fire from the last decade of the 21st century (2090-2099) for the RCP4.5 and RCP8.5 experiments compared to the historic period (1997-2006). The climate variables are mean annual temperature (MAT, °C), mean annual precipitation (MAP, mm/yr) and the ratio of actual to potential evapotranspiration (α). Fire danger is represented by the McArthur cumulative fire danger index (FDI). The vegetation parameters are tree cover (%) and fuel load (kg/m²), while fire is represented by burnt area (%). Colours show the absolute change and stippling shows the robustness of the signal (as measured by the standard deviation (sd) of the model results divided by the ensemble mean for each grid cell), where stippled areas indicate higher confidence in the signal.
Figure 5. Factors affecting regional changes in burnt area in northern (N), central (C), southwestern (SW) and southeastern (SE) Australia. The histograms show the mean change in burnt area (%), tree cover (%), minimum fuel moisture (i.e. the mean fuel moisture during the month with the lowest overall values of fuel moisture, %), coarse fuel (kg/m²) and fine fuel (kg/m²) in the last decade of the 21st century (2090-2099) for the RCP4.5 and RCP8.5 experiments compared to the historic period (1997-2006). The black bars show the standard deviation of the individual experiments.
The diagram shows the distribution of various variables across different regions and climate change scenarios (RCP4.5 and RCP8.5). The variables include Burnt Area, Tree Cover, Fuel Moisture, Coarse Fuel, and Fine Fuel. The regions represented are N (North), C (Central), SW (South West), and SE (South East). The data is visualized using bars and error bars to indicate variability.
Figure 6. Maps of the difference in burnt area (%), net primary production (NPP, kg C/m²) and tree cover (%) in the last decade of the 21st century (2090-2099) between the RCP simulations with fixed CO₂ and the simulations in which both climate and CO₂ were allowed to vary. Positive values therefore have the sense here of the impact of CO₂ fertilisation on the variable.
Figure 7. Maps of the ensemble changes in vegetation distribution during the last decade of the 21st century (2090-2099) for the RCP4.5 and RCP8.5 experiments compared to the historic period (1997-2006). To isolate the impact of CO₂ fertilisation on the vegetation, the results for the same decade of the RCP4.5 and RCP8.5 fixed-CO₂ experiments are also shown. The simulated abundance of individual plant functional types (PFTs) was converted to major vegetation types (biomes) using a modified version of the algorithm described in Prentice et al. (2011). The change in the area of each biome (Mkm²) between the last decade of the historic period and the last decade of the 21st century is shown in the box-and-whisker plots, where the black lines shows the median value, the box shows the interquartile range and the whiskers show the 95% range of the model values.
Figure 8. Impact of changes in climate, CO$_2$ and fire on plant functional types (PFTs) in regions where biomes remain unchanged by the end of the 21$_{st}$ century in the RCP4.5 and 8.5 scenario simulations. The plots show the change in the abundance of resprouting and non-resprouting trees (%) compared with changes in burnt area (%) and tree cover (%) within each of the five major biomes, grass and shrubland, tropical savanna, tropical forest, sclerophyll woodland and temperate forest.