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Future changes in climatic water balance determine potential for transformational shifts in Australian fire regimes

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Abstract

Most studies of climate change effects on fire regimes assume a gradual reorganization of pyrogeographic patterns and have not considered the potential for transformational changes in the climate-vegetation-fire relationships underlying continental-scale fire regimes. Here, we model current fire activity levels in Australia as a function of mean annual actual evapotranspiration (E) and potential evapotranspiration (E_0), as proxies for fuel productivity and fuel drying potential. We distinguish two domains in E, E_0 space according to the dominant constraint on fire activity being either fuel productivity (PL-type fire) or fuel dryness (DL-type fire) and show that the affinity to these domains is related to fuel type. We propose to assess the potential for transformational shifts in fire type from the difference in the affinity to either domain under a baseline climate and projected future climate. Under the projected climate changes potential for a transformational shift from DL- to PL-type fire was predicted for mesic savanna woodland in the north and for eucalypt forests in coastal areas of the south–west and along the Continental Divide in the south–east of the continent. Potential for a shift from PL- to DL-type fire was predicted for a narrow zone of eucalypt savanna woodland in the north–east.

1. Introduction

Fire is a profound organizing force for ecosystems (Bowman *et al* 2009), a significant contributor to global biogeochemical cycles (van der Werf *et al* 2010) and a major influence on human populations in fire-prone environments (Gibbons *et al* 2012, Chuvieco *et al* 2014, Moritz *et al* 2014). Projected changes in global fire patterns (Krawchuk *et al* 2009, Westerling *et al* 2011, Moritz *et al* 2012) in response to future climate, rising atmospheric [CO_2] and land use are highly uncertain, limiting our ability to predict the response of terrestrial ecosystems to global change.

Fires occur across the continents with characteristic distributions of size, intensity, frequency and season, forming a small number of distinct 'pyromes', or broad syndromes of fire regimes (Archibald *et al* 2013). How these syndromes emerge from interactions of climate, vegetation, land use and human behaviour remains incompletely understood, hindering the predictions from dynamic global vegetation models (DGVMs) and other approaches that seek to predict land surface dynamics under global change (Kelley and Harrison 2014, Scheiter *et al* 2014). Incomplete knowledge about the biophysical relationships that control global patterns of fire increases uncertainty about the potential for widespread fire regime shifts under altered future climates. So far, most studies have focused on quantifying changes in the frequency of fire occurrence under future climate conditions (Krawchuk *et al* 2009, Pechony and Shindell 2010, Moritz *et al* 2012), whereas the potential for transformational changes in the processes underlying continental-scale fire regimes is less clearly understood (but see e.g., Lindenmayer *et al* 2011, Cary *et al* 2012, Bowman *et al* 2014). Here, we propose a modelling framework for evaluating the potential for change in the average rate of burning (i.e. fire activity level) as well as for changes in fire type (i.e. transformational shifts) under altered future climates.

Fuel production and desiccation are the two fundamental processes underlying all fire regimes as fires will only burn across landscapes when there is sufficient fuel (i.e., combustible plant biomass) and when that fuel is dry enough to burn (Meyn *et al* 2007, Bradstock 2010). Frequencies of ignitions and favourable fire weather conditions also affect fire activity and behaviour once fuel load and fuel dryness constraints are overcome (Bradstock 2010). Thus fuel production and desiccation provide the functional platform on which potential fire activity is based and on which the influence of other factors, such as short term fluctuations in fire weather, variations in ignition and management activities, will be conditional. Thus an understanding of the relationship between fire activity and these two fundamental biophysical constraints on fire is necessary to delimit ecosystems where potential pathways of change under future climates may differ.

Essentially, fuel productivity and fuel dryness are a function of the local water and energy budgets available for the production and desiccation of plant biomass, and therefore a function of climate. Over annual or decadal time scales, the climatic water balance summarizes the simultaneous availability of biologically usable energy and water at a site (Budyko 1958, Stephenson 1998): $W = E + S$ and $E_0 = E + D$, where W is total precipitation infiltrating into the soil, E is actual evapotranspiration, and E_0 is potential evapotranspiration, while S and D are the mean annual climatic water surplus and deficit, respectively (all in mm yr^{-1}). At annual timescales actual evapotranspiration (E) is a reliable predictor of continental patterns of annual primary productivity (Rosenzweig 1968, Yang *et al* 2013) and hence a reasonable proxy for fuel production rates. The potential evapotranspiration (E_0) is an absolute measure of evaporative demand and proportional to energy available for desiccating live and dead fuels. Therefore, we hypothesized that continental variation in mean annual fire activity levels is well predicted by a combination of mean annual E and E_0 (Littell and Gwozdz 2011). If true this would provide an approach to evaluate the potential for incremental changes in mean annual fire activity levels under projected future climates. To evaluate potential for qualitative changes in the processes underlying continental-scale fire regimes ('transformational shifts', as developed in next paragraph) we focus on the relative importance of fuel productivity and fuel dryness constraints on fire activity levels.

As shown by Krawchuk and Moritz (2011), the relative importance of fuel productivity and fuel dryness constraints on global fire activity varies in a predictable way among the world's biomes according to their net primary productivity levels. Fuel productivity is the primary constraint on fire activity levels in low-productivity ecosystems with discontinuous vegetation cover such as semiarid woodlands (O'Donnell *et al* 2011). Fuel dryness, in turn, limits fire activity in high-productivity ecosystems (e.g., temperate closed forests) where fuels are abundant year-round but too wet to burn for much of the time (Bradstock 2010, Caccamo *et al* 2012, Archibald *et al* 2013). Since fuels are a derivative of vegetation type, we hypothesized that fuels would differ qualitatively with the relative importance of productivity and dryness constraints. Grasses and herbaceous plants can be expected to be the main source of fuel where productivity limits fire, and litter, foliage and fine branches from woody shrubs and trees where dryness limits fire activity, but this remains to be demonstrated. The combination of vegetation/fuel type and dominant constraint on fire activity sets important boundary conditions for other key characteristics of continental-scale fire regimes, such as typical fire intervals, intensities and season of burning (Archibald *et al* 2013, Murphy *et al* 2013, Whitman *et al* 2015). Given these climate-vegetation-fire relationships (Pausas and Paula 2012, Bowman *et al* 2014), a shift from one dominant climate constraint on fire activity to the other in response to altered climate conditions would represent a transformational shift in fire type and a qualitative change in ecological functioning. We hypothesized that environments characterized by either fuel productivity limitations on fire (PL-type fire) or fuel dryness limitations on fire (DL-type fire) occupy distinct climate domains that can be defined by a combination of mean annual E and E_0. If true this would provide an approach to evaluate potential for transformational shifts in fire type (i.e., from PL- to DL-type fire or vice versa) under projected climate change.

To test these hypotheses we analysed Australian patterns of fire activity, climate water balance and fuel types. Australia is a highly fire-prone continent; on average 500 000 km^2 or 7% of its land area is burned annually (Russell-Smith *et al* 2007, Giglio *et al* 2013), representing a nationally significant source of carbon emissions (Haverd *et al* 2013). Australia's fire regimes are highly diverse (Archibald *et al* 2013, Murphy *et al* 2013) and many remain relatively unmodified compared with those of fire-prone environments on other continents (Bradstock *et al* 2012). The paper first presents a modelling framework for quantification of the relative importance of fuel productivity (PL) and fuel dryness (DL) limitations on continental fire activity patterns and for the identification of the two corresponding climate domains, where either productivity-limited fire (PL) or dryness-limited fire (DL) prevails. We use quantile regression modelling to define how the upper limit of fire activity responds to fuel productivity and dryness and the corresponding domains of these controls on potential fire activity. We then demonstrate how this climate-fire model can be used with projections of future climate to assess the potential for incremental changes in fire activity levels and transformational shifts in fire type under projected climate conditions for the end of the 21st century.

2. Material and methods

2.1. Fire activity index

Gridded, 0.01° × 0.01° resolution (ca 1 km × 1 km), fire frequency data for 1997–2010 covering the Australian continent were obtained from the AusCover remote sensing data portal (http://www.auscover.org.au/node/58) of Terrestrial Ecosystem Research Network (TERN). Here, fire frequency was defined as the number of times a pixel has been affected by fire in the observation period 1997–2010. The fire frequency estimate was derived from manual mapping of fire affected areas at fortnightly time steps using continental imagery from the Advanced Very High Resolution Radiometer (AVHRR) (Turner *et al* 2012). The 0.01° × 0.01° resolution fire frequency data, with a range of 0 for unburned pixels to 14 for annually burned pixels, was used to calculate a fire activity index at 0.05° × 0.05° resolution with a data range of 0 to 1 by: (i) aggregating and summing values of 25 (i.e., 5 × 5) 0.01° pixels, and (ii) dividing resulting values by 350 (i.e., 14 years × 25 pixels). The resulting fire activity index, *F*, quantified the mean annual burn fraction of each 0.05° × 0.05° grid cell.

2.2. Climatic water balance, mean annual *E* and E_0

Gridded, 0.05° × 0.05° resolution (ca 5 km × 5 km), climate data covering the Australian continent, including daily precipitation (*P*) and minimum and maximum air temperature, were obtained from the SILO data base (Jeffrey *et al* 2001). The Modified Hargreaves equation (Droogers and Allen 2002) was used to quantify mean monthly potential evapotranspiration (E_0) from extraterrestrial radiation, mean daily temperature range and mean monthly rainfall. The Modified Hargreaves equation is recommended for predicting E_0, rather than the Penman–Monteith method, where accurate meteorological data are unavailable (Droogers and Allen 2002), such as in vast areas of inland Australia. Mean annual actual evapotranspiration (*E*) was estimated from mean annual *P* and E_0 using the semi-empirical model proposed by Budyko (1958):

$$E = P^*\left[\varnothing^*\tanh\left(\frac{1}{\varnothing}\right)(1-\exp(-\varnothing))\right]^{1/2} \quad (1)$$

where $\varnothing$ is the aridity index computed from mean annual *P* and E_0 ($\varnothing = E_0/P$).

The Budyko curve was developed for predicting mean annual runoff (*Q*) and actual evapotranspiration ($E = P - Q$) from large catchments and is widely used in hydroclimatology and water balance studies (Potter and Zhang 2009, Williams *et al* 2012).

2.3. Climate-fire model

The extent to which current fire activity is limited by fuel productivity or fuel dryness was quantified by modelling variation in the fire activity index as a function of mean annual *E* and E_0 over the same period (i.e., 1997–2010). A three-dimensional scatterplot of the data revealed strong increases of *F* with *E* and a humped relationship with E_0 (appendix S1 in supporting information). The limiting effect of *E* and E_0 on fire activity is best captured by the upper quantiles of *F*, because for those *F* observations we may assume that all other constraints that act on fire activity but are not explicitly included in the model (i.e. fire weather and ignitions) are non-limiting (Cade and Noon 2003). Lower quantiles of *F* may also show trends with *E* and E_0 and excellent fit to the data but do not provide the same level of inference about the fire-limiting effect of *E* and E_0 as for the upper quantiles (appendix S3). Importantly, prediction of future changes in the climatically determined fundamental domains of fire (i.e. fuel productivity versus fuel dryness) based on the upper limit of fire activity will be free of confounding influences, of for example, extant land use, fire management activities and ignition patterns. Use of a model for future projections of the changes to the climatically determined domain of fire, which implicitly incorporated these influences (i.e. at quantiles below the maximum) would require the unrealistic assumption that all other influences on fire would remain constant in the future. Our approach provides a pathway for a systematic, complementary exploration of the consequences for fire of changes in climate and other human influences.

The total data set for Australia consisted of 239 230 (0.05° × 0.05°) grid cells representing the total continental land area under native vegetation cover. A randomly selected sample of 50% of the data (119 615 grid cells) was used for model fitting, leaving the other 50% of the data for model validation (appendix S2). Using the 'quantreg' package in R (R Development Core Team 2015) a nonlinear model was fitted to the 0.99 quantile of the fire activity index, $F_{0.99}$, with mean annual *E* and E_0 as independent variables. A good fit was obtained for a model that combined two logistic terms:

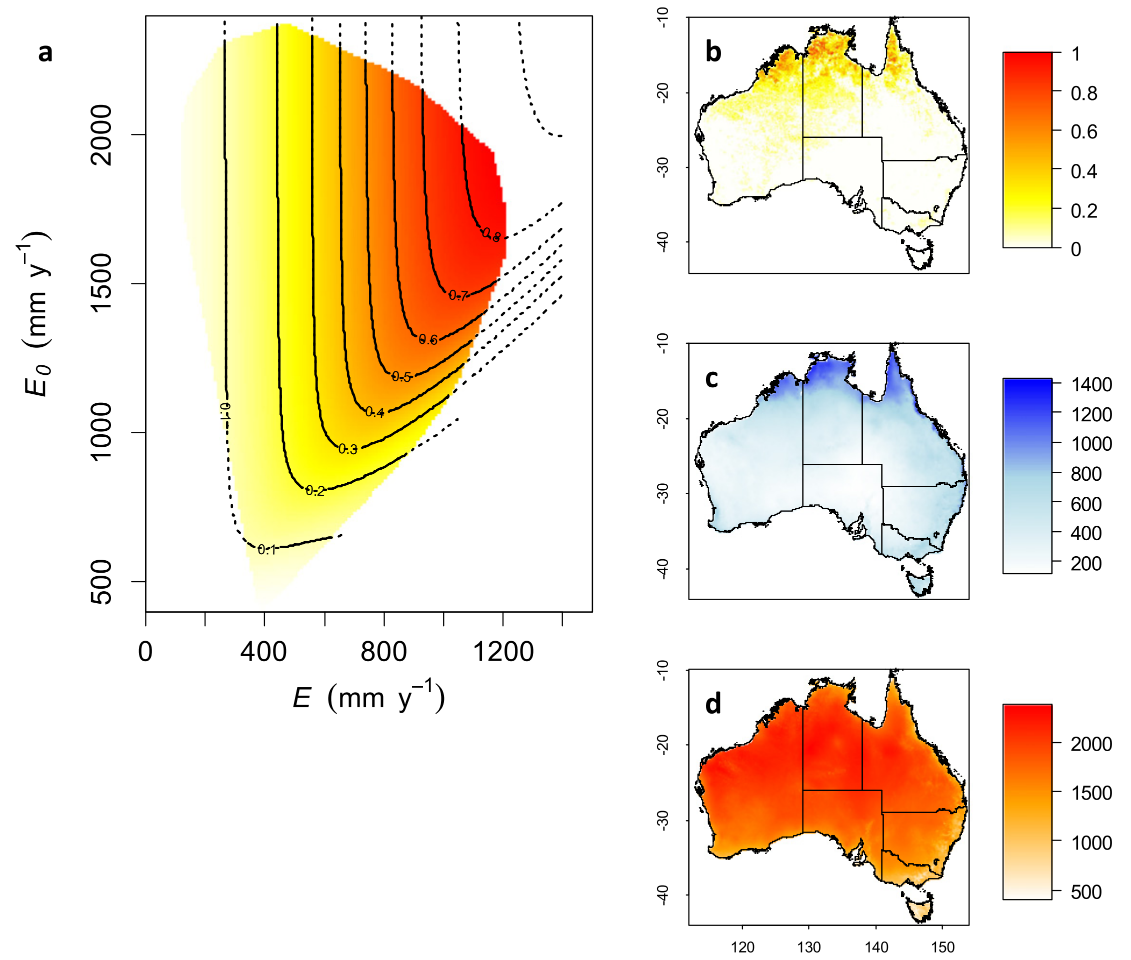

Figure 1. Climatic constraints of current fire activity in Australia. (a) Fitted 0.99 quantile surface of the fire activity index (1997–2010) as a function of mean annual actual evapotranspiration (E) and potential evapotranspiration (E_0). Model contours are dashed outside current climate envelope. Fire activity is low in temperate and hot arid environments (low E, low/high E_0) and highest in seasonally dry tropical environments that combine high E and very high E_0. (b) Mean annual fire activity index, (c) mean annual E and (d) E_0 in mm yr^{-1} over the 1997–2010 period.

$$F_{0.99} = \left[\frac{1}{1 + e^{aE+b}}\right]\left[\frac{1}{1 + e^{cD+d}}\right], \quad (2)$$

where, $F_{0.99}$ is the 0.99 quantile of the fire activity index, E and E_0 are mean annual actual and potential evapotranspiration in mm yr^{-1}, and $D = E_0 - E$ or mean annual climatic water deficit (Stephenson 1998), and a, b, c and d are fitted coefficients (appendix S2, table S1).

To minimize bias towards arid and semiarid climates in the fitted climate-fire model, we used the following bootstrap procedure: (i) the continental E, E_0 space was divided into 100 mm × 100 mm bins and all bins with a minimum of 10 grid cells identified ($n = 143$), (ii) a random sample (with replacement) of 10 grid cells was drawn from these bins, and (iii) equation (2) was fitted to the sample data. This procedure was run 1000 times to generate 1000 response surfaces from which a mean response surface was calculated (figure 1(a)).

We hypothesized that there would be two distinct domains for the climate–fire relationship: (i) environments of PL-type fire characterized by $F_{0.99}$ increasing predominantly with E, and (ii) environments of DL-type fire characterized by $F_{0.99}$ increasing predominantly with E_0, plus a narrow transition zone where $F_{0.99}$ was likely to be equally sensitive to both E and E_0. We tested this hypothesis by graphing quantitative contours of $F_{0.99}$ in the two dimensional space defined by axes representing variation in mean annual E and E_0. For the sake of simplicity, we ignored the transition zone and divided the E, E_0 space into two domains depending on the direction of the gradient of the fitted $F_{0.99}$ response surface. After rasterizing the $F_{0.99}$ response surface into 10 mm × 10 mm E, E_0 grid cells the local slope direction (i.e. aspect) of every grid cell was decomposed into an E component, $g_E = -\sin(a_F)$, and a E_0 component, $g_{E_0} = -\cos(a_F)$, where a_F is the aspect of the $F_{0.99}$ response surface in radians. All E, E_0 grid cells where $g_E > g_{E_0}$ were classified as being in the domain of PL-type fire and all others, where $g_E \leqslant g_{E_0}$, as being in the domain of DL-type fire. This classification was applied to each of the 1000 fitted $F_{0.99}$ response surfaces yielding 1000 classifications from which a probability of being classified as PL- or

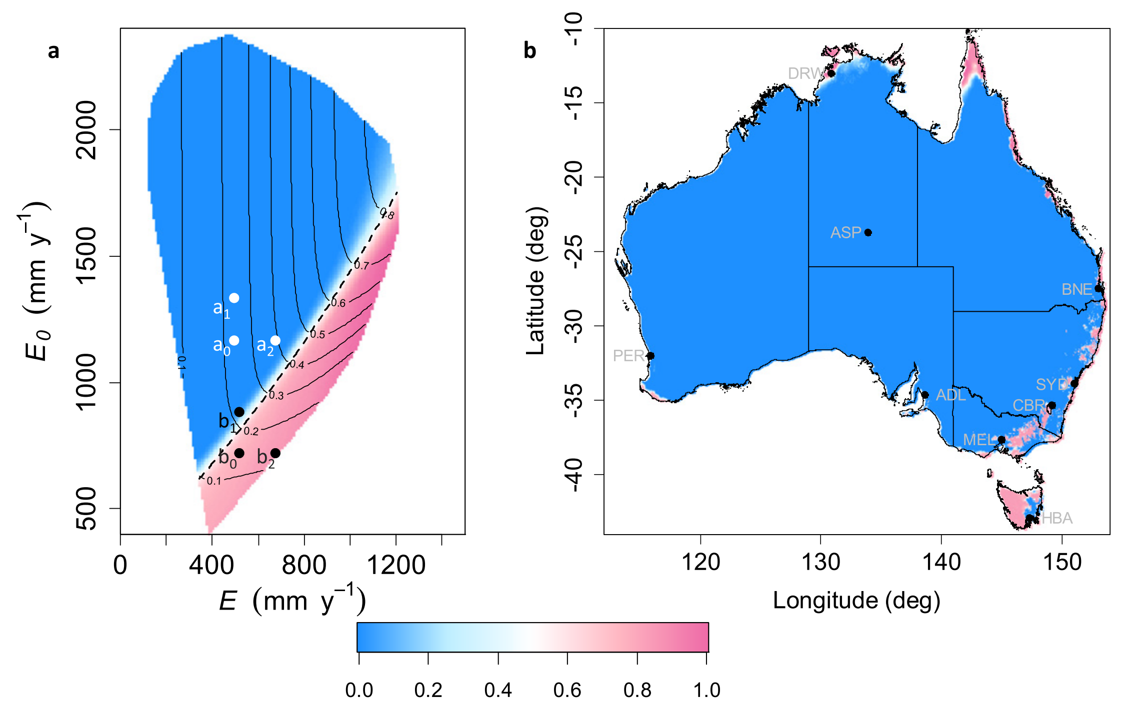

Figure 2. Climatic domains of the two main fire types in Australia. (a) Mean annual actual evapotranspiration (E) and potential evapotranspiration (E_0) determine the potential level of fire activity (black contours, see equation (2)) and the probability for being in the domains of fuel production limited fire (PL-type) or fuel dryness limited fire (DL-type), indicated by blue and pink tones respectively. Strictly, the colour scale indicates probability of DL-type, which equals 1 minus probability of PL-type. The white area and the dashed black line indicate the transition between the two domains (i.e., probability for either domain = 0.5). The white dot (a_0) shows the current position of an arid environment, where fire activity would respond strongly to increasing $E(a_2)$ but not to increasing $E_0(a_1)$. The black dot (b_0) shows the current position of a more humid temperate environment, where an increase in $E_0(b_1)$ would imply a strong increase in fire activity and create potential for a transformational fire regime shift, while an increase in $E(b_2)$ would have a minor incremental effect on fire activity. (b) Geographical distribution in Australia of the probability for being in the domains of PL- or DL-type fire, indicated by blue and pink tones, according to the fitted 0.99 quantile surface of the fire activity index (figure 1(a)) for the 1986–2005 baseline period. Black dots indicate locations of major cities (ADL: Adelaide, ASP: Alice Springs, BNE: Brisbane, CBR: Canberra, DRW: Darwin, HBA: Hobart, MEL: Melbourne, SYD: Sydney, PER: Perth).

DL-domain could be calculated for every E, E_0 grid cell (figure 2(a)). These probabilities were mapped to geographical space for the 1986–2005 baseline climate (figure 2(b)) and future climate using gridded mean annual E and E_0 for the corresponding period. Gradients and aspects of the $F_{0.99}$ response surface were computed using terrain analysis functions available in the 'raster' package for R (R Development Core Team 2015), while the 'intamap' package was used for spatial interpolation of PL- and DL-domain probabilities.

2.4. Fuel types and tree cover

The relationship between the dominant climate constraint on fire (i.e., fuel productivity or fuel dryness) and fuel type (i.e., grass versus litter from woody plants) was investigated in two steps. We first used an existing field data set of fuel loads and ground-based observations of tree cover for 113 sites across Australia (D M J S Bowman, B P Murphy and M A Cochrane, unpublished data, appendix S5, figure S7) to analyse the relationship between fuel composition and tree cover. We then used the moderate resolution imaging spectroradiometer (MODIS) data set of remotely sensed tree cover (MOD44B Collection 4 product, version 3, 500 m resolution) to analyse how continental tree cover varies with the modelled probability of being in the domain of PL- or DL-type fire as a test of our hypothesis that the relative strength of fuel productivity and fuel dryness constraints on fire is related to fuel composition. Tiled MOD44B data for the Australian continent was mosaicked to one layer and resampled to the 0.05° × 0.05° grid used for the climate variables (appendix S5, figure S7). The relationship between MODIS tree cover percentage and probability of classification to the domain of DL-type fire was analysed by binning all Australian grid cells (n = 239 230) in one of five probability classes (i.e. from 0 to 1 in 0.2 increments) and quantifying the distribution of MODIS tree cover percentage for each class (figure 3(b)). The relationship between MODIS tree cover percentage and remotely sensed fire activity across Australia was analysed using nonparametric quantile regression with the 'quantreg' package in R (R Development Core Team 2015).

2.5. Projected climate

Projected changes in mean monthly precipitation and temperatures for 2080–2099 were obtained from the climate change in Australia data portal (CSIRO and

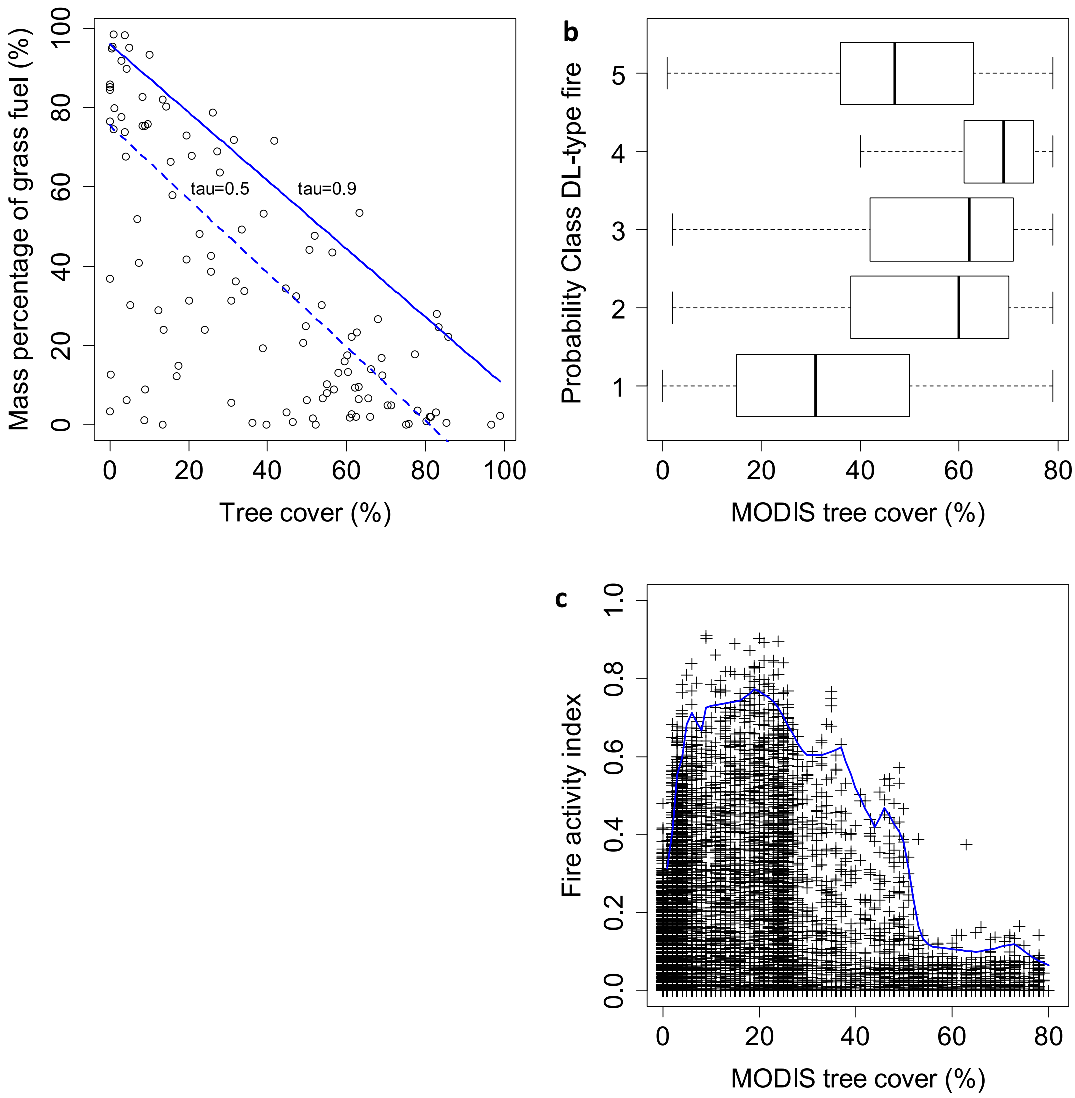

Figure 3. Tree cover, fuel types and climate constraints on fire activity in Australia. (a) Percentage of grass in dead fuels as a function of tree cover for field sites across Australia ($n = 113$), with fitted linear models for 0.90 and 0.50 quantiles. (b) Box-whisker plot showing distributions of observed MODIS tree cover percentage for five classes of modelled probability of being in domain of DL-type fire; classes 1–5, indicate probabilities from 0.0 to 1.0 in 0.2 increments. (c) Mean annual fire activity index against MODIS tree cover percentage, with blue curve for the fitted 0.99 quantile.

Bureau of Meteorology 2015b). As our main goal was to demonstrate how our climate-fire model could be used to assess potential for incremental and transformational changes in fire activity and fire type, we selected projections from one CMIP5 (Coupled-Model Intercomparison Project) model and one representative concentration pathway (RCP). A full CMIP5 ensemble analysis was beyond the scope of the present paper.

The ACCESS1-0 model has been shown to simulate historical climate in Australia particularly well (CSIRO and Bureau of Meteorology 2015a). We obtained ACCESS1-0 projections of change with respect to 1986–2005 baseline in mean monthly precipitation and temperatures by 2080–2099 under RCP4.5. Under RCP4.5, radiative forcing of the global climate system is assumed to stabilize at ~4.5 W m^{-2} after 2100, which is in the lower half of the range represented by the four RCPs (van Vuuren *et al* 2011). The projected changes in precipitation and temperatures were calculated using the 'time-slice' method applying the current standard baseline period 1986–2005 (IPCC 2013, p 1031). This involves subtracting a future 20 year averaged value as simulated by the selected climate model from the 20 year averaged baseline (1986–2005) from the same model. The difference is presented in degrees Celsius for temperature variables and per cent change for other variables. (CSIRO and Bureau of Meteorology 2015a). The projected change grids had been resampled by the data provider using bilinear interpolation from the native model resolution of $1.00° \times 1.00°$ to the $0.05° \times 0.05°$ grid used in this study. Future climatologies for mean monthly precipitation, and minimum and maximum air temperature were computed by adding the projected changes for 2080–2099 to gridded historical climate data (1986–2005) from the SILO data base (Jeffrey *et al* 2001). Projected mean annual E_0 and E for 2080–2099 was calculated from projected climate inputs as described above for the baseline climate.

2.6. Climate change impact assessment

The potential for future changes in fire activity and in the probability of falling in the domains of PL- or DL-type fire was assessed by comparing each grid cell's E, E_0 coordinates for the 20 year baseline period (1986–2006) with those projected for the future period (2080–2099). Climate conditions during the 1986–2005 baseline period differed slightly from those during the climate-fire modelling period 1997–2010 (appendix S4, figure S6). Potential change in predicted $F_{0.99}$ was computed from the difference between the predicted $F_{0.99}$ for each grid cell's E, E_0 coordinates under 1986–2005 baseline climate and the projected 2080–2099 climate. Similarly, the potential for a shift from PL- to DL-type fire or vice versa was assessed for every grid cell from differences between baseline and future probabilities of being classified to the domain of PL- or DL-type fire, which in turn are a function of the uncertainty about the form of the fire response surface (as estimated from 1000 model fits) and baseline and future E, E_0 coordinates.

3. Results

3.1. Climate-fire model

Current patterns of fire activity in Australia based on remote sensing of fire-affected areas were a nonlinear, yet highly predictable, function of mean annual E and E_0 (figure 1(a)). The fitted model for $F_{0.99}$ (equation (2)) explained a large proportion of the continental variation in maximum fire activity levels for a given combination of mean annual E and E_0 (adj. R^2: 0.89, RMSE: 0.09) and model residuals were close to normally distributed (appendix S2). Low levels of $F_{0.99}$ were observed, as expected, in the driest and coldest environments of the continent characterized by low E and low E_0, respectively. The highest levels of fire activity, with $F_{0.99}$ exceeding 0.8, was recorded in environments of intermediate to high E and very high E_0 corresponding to the tropical savannas of northern Australia, where the current fuel production and fuel desiccation potential supported (bi-) annual burning (Russell-Smith *et al* 2007). The form of the fitted $F_{0.99}$ response surface (figure 2(a)) supported the hypothesized dichotomy of two distinct domains of climate limitation on fire activity: (i) relatively hot and dry environments where $F_{0.99}$ was more sensitive to E than to E_0 (i.e., PL-type fire), and (ii) relatively cool and humid environments where $F_{0.99}$ was more sensitive to E_0 than to E (i.e., DL-type fire). Interestingly, the transition between the domains of PL- and DL-type fire was predicted to fall at a nearly constant ratio of E_0 and E of about 1.46 ± 0.03 (appendix S2, figure S3). This makes sense as the amount of energy required to dry out fuel to ignitable levels should be proportional to fuel productivity. When mapped to geographical space the two domains are sharply separated, with PL-type fire prevailing throughout the interior of the continent and DL-type fire restricted to the most humid coastal regions (figure 2(b)).

3.2. Fuel type, tree cover and climate constraints on fire activity

Field observations of fuel composition and continental patterns of tree cover fitted the hypothesized pattern: high proportions of grassy fuel were found in the domain of PL-type fire (appendix S5, figure S7(a)), while tree cover, which is inversely related to the maximum grass component of fuels (figure 3(a)), was significantly higher in the domain of DL-type fire than in the domain of PL-type fire (appendix S5, figure S7(b)), with a shift in the probability of being in the domain of DL-type fire observed at MODIS tree cover of circa 60% (figure 3(b)). Tree cover was not only a predictor of fuel type but also strongly related to the maximum level of fire activity in the landscape. Across Australia fire activity was highest in ecosystems with less than 30% tree cover, decreased gradually for ecosystems with tree cover between 30% and 50%, and dropped to the lowest levels in ecosystems with tree cover exceeding about 55% (figure 3(c)).

3.3. Impact of projected climate change

Under RCP4.5 the future climate in Australia was projected to become substantially drier in much of south-western Australia, the Kimberley, Tasmania, eastern Victoria and south-eastern Queensland, while substantial increases in mean annual precipitation were projected for Northern Queensland, and in parts of the arid interior and along the east coast of New South Wales (figure 4(a)). By 2080–2099, mean annual potential evapotranspiration, was projected to increase in much of the continent, particularly in the southwest, and to decrease in Northern Queensland (figure 4(b)). The projected changes in mean annual precipitation and potential evapotranspiration translated into proportionally strong changes in mean annual E (figure 4(c)).

Combining the $F_{0.99}$ response surface (figure 1(a)) with the projected change in mean annual E and E_0 yielded strong predicted increases in potential fire activity for Northern Queensland, parts of the northern interior, and the south–east of the continent, while decreases in the upper quantiles of fire activity were predicted for part of the south–west, southern Kimberley and Cape York (figure 4(d)). Our analysis showed that under projected future climate conditions there were some areas with potential for transformational shifts in fire type, but that potential for such

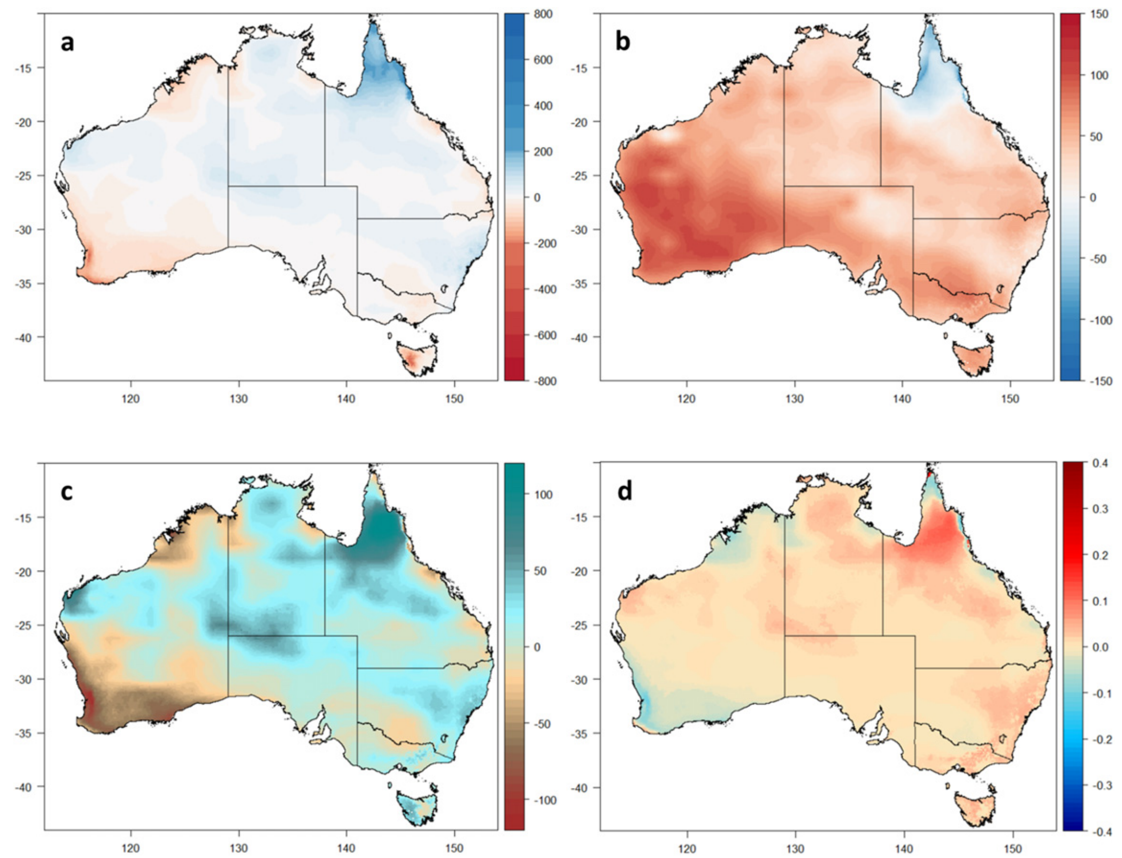

Figure 4. Projected changes in climate and fire activity under representative concentration pathway (RCP) 4.5 by 2080–2099 (1986–2005 baseline climate). The four panels show absolute change in mean annual (a) precipitation, P (mm yr^{-1}), (b) potential evapotranspiration, E_0 (mm yr^{-1}), (c) actual evapotranspiration, E (mm yr^{-1}), and (d) 0.99 quantile of the fire activity index, $F_{0.99}$. Changes were calculated as projected 2080–2099 climate minus 1986–2005 baseline climate. Note that panels (a) and (b) have reverse colour scales.

transformation was restricted to relatively small areas and to be predominantly from DL- to PL-type fire (figure 5, table 1).

In tropical Northern Australia, potential for a shift from DL- to PL-type fire was predicted for relatively small areas (ca 7624 km^2 in total) of mesic eucalypt savanna woodland in the Northern Territory where the projected increases in E_0 would cause fuels to dry-out earlier in the dry season and mean annual fire activity levels to increase (figure 5(a), table 1). Potential for a shift from PL- to DL-type fire was predicted for a narrow band of eucalypt savanna woodland in the Cape York Peninsula and along the western slopes of the Great Dividing Range in Northern Queensland (ca 5646 km^2 in total) (figure 5(a)). Potential mean annual fire activity in these areas is currently very high ($F_{0.99} \approx 0.7$); future climate conditions were projected to become wetter and warmer (figure 4), creating potential for increased fuel production, an increase in fire activity and fuel dryness becoming the dominant climate constraint on fire (figure 5(a), table 1).

In south–east Australia, transformational shifts from DL- to PL-type fire were projected for a scattering of small areas mostly along the Continental Divide (ca 18 380 km^2 in total) characterized by temperate eucalypt forest. In these areas climate conditions for 2080–2099 were projected to become warmer with significant increases in E_0, creating potential for increasing mean annual levels of fire activity and for fuel productivity rather than fuel dryness becoming the main limiting factor for fire activity (figure 5(b), table 1). In the coastal zone of south–west Western Australia an area of ca 3975 km^2 of predominantly temperate eucalypt forest was also projected to change from DL- to PL-type fire while mean annual fire activity levels were projected to increase slightly. These changes were predicted to result from drier future climate conditions caused by a decrease in mean annual precipitation and an increase in mean annual E_0 (figure 4, table 1).

4. Discussion

The spatial pattern of the upper limit of mean annual fire activity was strongly related to mean annual climate conditions in Australia, consistent with previous studies of continental and global fire patterns (e.g., Krawchuk *et al* 2009, Archibald *et al* 2010). Significantly, 89% of the spatial variation in the 0.99 quantile of mean annual fire activity levels in Australia

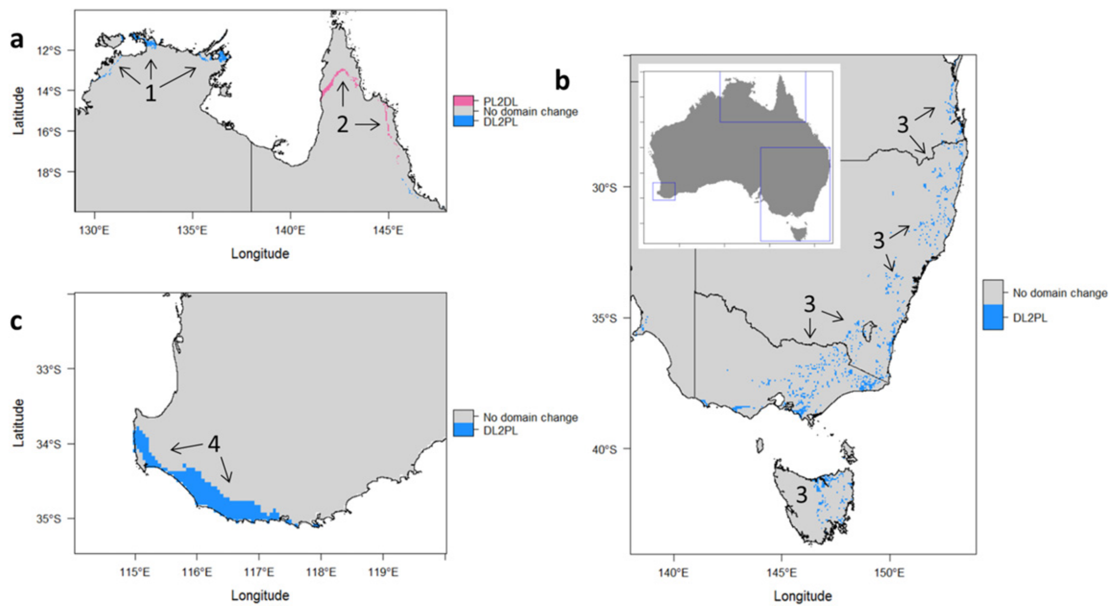

Figure 5. Potential changes in domains of fuel production limited (PL-type) fire or fuel dryness limited (DL-type) fire under projected climate conditions for 2080–2099 (RCP 4.5, 1986–2005 baseline climate) in Northern Australia (a), South–east Australia (b), and South–west Australia (c). In blue coloured areas there is potential for change from the domain of DL- to PL-type fire. In pink coloured areas there is potential for change from the domain of PL- to DL-type fire, while no domain change is projected for grey areas. Blue boxes in the inset map show approximate locations of the three regions of Australia. Numbers 1–4 are used to refer to areas of potential change in table 1.

was explained by two components of the climatic water balance, mean annual actual evapotranspiration (E) and potential evapotranspiration (E_0). We proposed to model fire activity as a function of the climatic water balance terms E and E_0, rather than the more commonly used mean annual or monthly precipitation and temperature (Spessa *et al* 2005, Daniau *et al* 2012, Batllori *et al* 2013), because E and E_0 are more directly related to a site's water and energy constraints on fuel production and fuel desiccation (Di Bella *et al* 2006, Littell and Gwozdz 2011, Parks *et al* 2014); the resulting climate-fire model, though statistical, has a sound biophysical basis (Bradstock 2010) and provided an excellent fit to the data.

As expected, fire activity was found to be lowest where either fuel productivity ($\propto E$) or fuel dryness constraints on fire ($\propto E_0$) are strong and highest where favourable conditions for both fuel production and desiccation are met. Our hypothesis that the relative importance of fuel productivity and fuel dryness constraints on fire activity is correlated with continental variation in fuel composition and tree cover was also confirmed by our analyses. Environments with low tree cover and dominated by grassy fuels, which prevail in most of Australia (Murphy *et al* 2013), were shown to be associated with a predominance of fuel productivity constraints on fire activity (PL-type fire), while environments with high tree cover and litter fuels were associated with strong fuel dryness constraints on fire (DL-type fire). The finding that tree cover and fuel type in Australia varied consistently with E and E_0 supports Stephenson's (1998) proposed use of the climatic water balance as a biologically meaningful predictor of vegetation composition at (sub-)continental scales.

Our results demonstrated that the climatic water balance sets important boundary conditions for key aspects of fire regimes (e.g., fire activity levels and return intervals, intensity range, season) through its influence on the type of fuel and on the frequency/seasonality with which fuel load and dryness limitations on fire are overcome under a given climate. The consistency and predictability with which these fire and fuel characteristics vary with position in E, E_0 space provides a robust framework to objectively evaluate potential for incremental changes in upper quantiles of fire activity levels as well as for qualitative shifts in the processes that underlie fire regimes under altered future climate conditions. As noted, this provides potential for evaluation of the potential for changes in fire regimes as a function of climatic change that are largely independent of likely changes in human activity.

Though the concept of variable productivity and dryness constraints on fire activity has been quantified before (Meyn *et al* 2007, Littell *et al* 2009, Krawchuk and Moritz 2011, Batllori *et al* 2013, Pausas and Ribeiro 2013, Bistinas *et al* 2014, Bowman *et al* 2014), we provide the first quantitative evidence that the continental-scale dichotomy of PL- and DL-type fire may be determined by the climatic water balance. Importantly, the analysis demarcates clear climatic and geographical boundaries between these different fire types. Such boundaries also correspond, according to

Table 1. Climatic water balance, fire activity and fire type for 4 dispersed areas in North, Southeast and Southwest Australia where projected climate change under RCP4.5 is predicted to create potential for transformational shifts from the domain of fuel dryness constraints on fire (DL-type) to the domain of fuel productivity constraints on fire (PL-type) or vice versa by 2080–2099; these shifts are referred to as DL2PL and PL2DL, respectively.

			Baseline 1986–2005				Projected 2080–2099				
ID.	Tree cover %	FRN	P	E_0	E	$F_{0.99}$	P	E_0	E	$F_{0.99}$	Domain change
1	15–33	2	1327–1385	1266–1341	900–943	0.56–0.62	1298–1367	1331–1412	914–966	0.61–0.66	DL2PL
2	25–35	2	1266–1521	1319–1593	891–1084	0.59–0.77	1489–1702	1400–1674	994–1175	0.66–0.81	PL2DL
3	66–78	15	921–1143	941–1108	646–777	0.29–0.43	922–1144	1041–1232	677–827	0.36–0.52	DL2PL
4	63–73	15	1088–1158	1034–1088	747–766	0.37–0.41	909–966	1109–1165	701–724	0.40–0.43	DL2PL

Note. The locations of these areas, numbered 1–4, are shown in figure 5. The symbols P, E_0 and E are mean annual precipitation, potential evapotranspiration and actual evapotranspiration in mm yr^{-1}, and $F_{0.99}$ is the 0.99 quantile of the fire activity index, for 1986–2005 baseline and 2080–2099 projections. Current MODIS tree cover percentage is also listed. Value ranges are the 25% and 75% quantiles of the grid cells in the indicated areas. FRN refers to Murphy *et al*'s (2013) fire regime niches. FRN 2: Eucalypt savanna woodland (monsoon tropical); FRN 15: Eucalypt forest (temperate).

expectations based on inherent fuel type, with different Australian vegetation communities and associated fire regime syndromes (Bradstock *et al* 2012, Murphy *et al* 2013).

The proposed biophysical framework was built from first principles of how climatic energy and water balances interact at annual to decadal time scales to constrain fuel types and their flammability (Stephenson 1998). These principles should also hold for future environments in Australia and globally (e.g., Parks *et al* 2014) and therefore provide a robust model for assessing the potential for fire regime shifts under 21st century climate projections. Moreover, by modelling fire types as a function of the climatic water balance our framework is, in principle, well-suited to evaluating changes in fire that may come about through changes in fuel productivity per unit of water use (i.e., water use efficiency, WUE) under elevated atmospheric CO_2 concentrations (Leakey *et al* 2009). CO_2-driven increases in ecosystem-level WUE could lower fuel-productivity constraints on fire activity in environments of PL-type fire, particularly in temperate Australia where C3 grasses prevail (Murphy and Bowman 2007), but concurrent warming and associated increases in atmospheric water demand could offset CO_2-related fuel productivity gains (Morgan *et al* 2011). In environments of DL-type fire, CO_2-driven increases in WUE are unlikely to affect fire activity levels via an increase in fuel productivity but could have an effect via changes in the timing and/or duration of periods of low canopy water content. The form of the $F_{0.99}$ response surface (figure 1(a)) and therefore the climatic boundaries of the fire type domains (figure 2) could change if elevated atmospheric CO_2 would alter the competitive relations between grasses and woody plants in fire-prone ecosystems (e.g., Bond and Midgley 2012, Kelley and Harrison 2014).

Though our modelling framework has a biophysical basis, our assessment of potential fire regime shifts due to climate change is essentially a space-for-time substitution and has the associated limitations such as: (i) the inability to predict a response to novel future climates (Williams and Jackson 2007, Blois *et al* 2013), (ii) the inability to account for the potentially very different time scales with which vegetation composition, tree cover, fuel type, fuel productivity and fuel dryness may respond to climate change across soil types (Krawchuk and Moritz 2014), or (iii) the inability to resolve transient ecosystem dynamics or novel outcomes of interacting ecosystem components (Bowman *et al* 2014). Our predictions of fire regime shifts therefore focused on evaluating whether projected changes in the climatic water balance would imply a move across the climatic boundary between DL- and PL-type fire. Where such a domain shift is climatically possible we assume that there is also potential for significant changes in fuel type and related fire regime characteristics (e.g., fire interval, intensity, size, season) to develop over long time scales (>>decades), but our modelling framework cannot resolve the actual trajectory or rate of change. These predictions could inform more complex modelling approaches such as DGVMs that do represent the transient dynamics of ecosystem change.

Our analysis suggested that under RCP4.5 projected changes in the climatic water balance by the end of the 21st century are of a magnitude and direction that could cause significant change in upper quantiles of fire activity levels ($F_{0.99}$) in about a quarter of the continent (figure 4), with increases predicted for 20% of the continent and decreases for 6% of the land area. These findings are consistent with the nature and magnitude of changes in annually burnt area predicted by the LPX-Mv1 DGVM under RCP4.5 for the end of the 21st century (Kelley and Harrison 2014). Our analysis showed the potential for transformational fire regime shifts to be restricted to relatively small areas on steep environmental gradients (figure 5). Though the likelihood of these changes remains to be quantified by a full ensemble analysis, our results strongly indicate that even under a moderate RCP there may be substantial change in fire activity over vast areas with potential implications for continental carbon fluxes (Haverd *et al* 2013), conservation of biodiversity and ecosystem services (Morton *et al* 2009), and risk of loss of life and property in the more densely populated areas (Chuvieco *et al* 2014, Moritz *et al* 2014).

Our prediction of the locations in Australia where there is potential for transformational fire regime shifts (figure 5) is conditional on the specific climate projection used in this study. However, because the boundary between the domains of DL- and PL-type fire is very sharp and well-defined, both climatically and geographically (figure 2), we can have confidence that transformational fire regime shifts will most likely occur in areas located near or within the transition zone, irrespective of the climate change scenario. Since that transition zone falls on relatively steep sections of the continental gradients of E and E_0 (figure 2(b)) we infer that transformational fire regime shifts are unlikely in the vast majority of the continent. This insight is useful as it allows further research into transformational fire regime shifts to focus on a small number of sensitive environments.

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References

Archibald S, Lehmann C E R, Gómez-Dans J L and Bradstock R A 2013 Defining pyromes and global syndromes of fire regimes *Proc. Natl Acad. Sci.* **110** 6442–7

Archibald S, Nickless A, Govender N, Scholes R J and Lehsten V 2010 Climate and the inter-annual variability of fire in southern Africa: a meta-analysis using long-term field data and satellite-derived burnt area data *Glob. Ecol. Biogeogr.* **19** 794–809

Batllori E, Parisien M-A, Krawchuk M A and Moritz M A 2013 Climate change-induced shifts in fire for Mediterranean ecosystems *Glob. Ecol. Biogeogr.* **22** 1118–29

Bistinas I, Harrison S P, Prentice I C and Pereira J M C 2014 Causal relationships versus emergent patterns in the global controls of fire frequency *Biogeosciences* **11** 5087–101

Blois J L, Williams J W, Fitzpatrick M C, Jackson S T and Ferrier S 2013 Space can substitute for time in predicting climate-change effects on biodiversity *Proc. Natl Acad. Sci. USA* **110** 9374–9

Bond W J and Midgley G F 2012 Carbon dioxide and the uneasy interactions of trees and savannah grasses *Phil. Trans. R. Soc.* B **367** 601–12

Bowman D *et al* 2009 Fire in the Earth system *Science* **324** 481–4

Bowman D M J S, Murphy B P, Williamson G J and Cochrane M A 2014 Pyrogeographic models, feedbacks and the future of global fire regimes *Glob. Ecol. Biogeogr.* **23** 821–4

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

Bradstock R A, Gill A M and Williams R J 2012 *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World* (Melbourne: CSIRO)

Budyko M I 1958 *The Heat Balance of the Earth's Surface* (Washington, DC: The US Dept. of Commerce)

Caccamo G, Chisholm L A, Bradstock R A and Puotinen M L 2012 Using remotely-sensed fuel connectivity patterns as a tool for fire danger monitoring *Geophys. Res. Lett.* **39** L01302

Cade B S and Noon B R 2003 A gentle introduction to quantile regression for ecologists *Frontiers Ecol. Environ.* **1** 412–20

Cary G J, Bradstock R A, Gill A M and Williams R J 2012 *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World* ed R A Bradstock *et al* (Melbourne: CSIRO) pp 149–69

Chuvieco E, Martínez S, Román M V, Hantson S and Pettinari M L 2014 Integration of ecological and socio-economic factors to assess global vulnerability to wildfire *Glob. Ecol. Biogeogr.* **23** 245–58

CSIRO and Bureau of Meteorology 2015a *Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report* CSIRO and Bureau of Meteorology, Australia p 222 (www.climatechangeinaustralia.gov.au/media/ccia/2.1.5/cms_page_media/168/CCIA_2015_NRM_TR_Front_Index.pdf)

CSIRO and Bureau of Meteorology 2015b *Climate Change in Australia website* (www.climatechangeinaustralia.gov.au/en/)

Daniau A L *et al* 2012 Predictability of biomass burning in response to climate changes *Glob. Biogeochem. Cycles* **26** GB4007

Di Bella C M, Jobbágy E G, Paruelo J M and Pinnock S 2006 Continental fire density patterns in South America *Glob. Ecol. Biogeogr.* **15** 192–9

Droogers P and Allen R 2002 Estimating reference evapotranspiration under inaccurate data conditions *Irrigation Drainage Syst.* **16** 33–45

Gibbons P, van Bommel L, Gill A M, Cary G J, Driscoll D A, Bradstock R A, Knight E, Moritz M A, Stephens S L and Lindenmayer D B 2012 Land management practices associated with house loss in wildfires *PloS One* **7** e29212

Giglio L, Randerson J T and van der Werf G R 2013 Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4) *J. Geophys. Res.: Biogeosci.* **118** 317–28

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 and Sherman B 2013 The Australian terrestrial carbon budget *Biogeosciences* **10** 851–69

IPCC 2013 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker *et al* (Cambridge: Cambridge University Press) p 1535

Jeffrey S J, Carter J O, Moodie K B and Beswick A R 2001 Using spatial interpolation to construct a comprehensive archive of Australian climate data *Environ. Modelling Softw.* **16** 309–30

Kelley D I and Harrison S P 2014 Enhanced Australian carbon sink despite increased wildfire during the 21st century *Environ. Res. Lett.* **9** 104015

Krawchuk M A and Moritz M A 2011 Constraints on global fire activity vary across a resource gradient *Ecology* **92** 121–32

Krawchuk M A and Moritz M A 2014 Burning issues: statistical analyses of global fire data to inform assessments of environmental change *Environmetrics* **25** 472–81

Krawchuk M A, Moritz M A, Parisien M-A, Van Dorn J and Hayhoe K 2009 Global pyrogeography: the current and future distribution of wildfire *PLoS One* **4** e5102

Leakey A D B, Ainsworth E A, Bernacchi C J, Rogers A, Long S P and Ort D R 2009 Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE *J. Exp. Bot.* **60** 2859–76

Lindenmayer D B, Hobbs R J, Likens G E, Krebs C J and Banks S C 2011 Newly discovered landscape traps produce regime shifts in wet forests *Proc. Natl Acad. Sci. USA* **108** 15887–91

Littell J S and Gwozdz R B 2011 *The Landscape Ecology of Fire* ed D McKenzie *et al* (Dordrecht: Springer) pp 117–39

Littell J S, McKenzie D, Peterson D L and Westerling A L 2009 Climate and wildfire area burned in western US ecoprovinces, 1916–2003 *Ecol. Appl.* **19** 1003–21

Meyn A, White P S, Buhk C and Jentsch A 2007 Environmental drivers of large infrequent wildfires: emerging conceptual model *Prog. Phys. Geogr.* **31** 287–312

Morgan J A, LeCain D R, Pendall E, Blumenthal D M, Kimball B A, Carrillo Y, Williams D G, Heisler-White J, Dijkstra F A and West M 2011 C4 grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland *Nature* **476** 202–5

Moritz M A *et al* 2014 Learning to coexist with wildfire *Nature* **515** 58–66

Moritz M A, Parisien M-A, Batllori E, Krawchuk M A, Van Dorn J, Ganz D J and Hayhoe K 2012 Climate change and disruptions to global fire activity *Ecosphere* **3** art49

Morton S R *et al* 2009 The big ecological questions inhibiting effective environmental management in Australia *Austral Ecol.* **34** 1–9

Murphy B P and Bowman D M J S 2007 Seasonal water availability predicts the relative abundance of C3 and C4 grasses in Australia *Glob. Ecol. Biogeogr.* **16** 160–9

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 and Bowman D M J S 2013 Fire regimes of Australia: a pyrogeographic model system *J. Biogeogr.* **40** 1048–58

O'Donnell A J, Boer M M, McCaw W L and Grierson P F 2011 Vegetation and landscape connectivity control wildfire intervals in unmanaged semi-arid shrublands and woodlands in Australia *J. Biogeogr.* **38** 112–24

Parks S A, Parisien M-A, Miller C and Dobrowski S Z 2014 Fire activity and severity in the western US Vary along proxy gradients representing fuel amount and fuel moisture *PloS One* **9** e99699

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

Pausas J G and Ribeiro E 2013 The global fire-productivity relationship *Glob. Ecol. Biogeogr.* **22** 728–36

Pechony O and Shindell D T 2010 Driving forces of global wildfires over the past millennium and the forthcoming century *Proc. Natl Acad. Sci.* **107** 19167–70

Potter N J and Zhang L 2009 Interannual variability of catchment water balance in Australia *J. Hydrol.* **369** 120–9

R Development Core Team 2015 *R: A Language and Environment for Statistical Computing* version 3.2.0 (Vienna: R Foundation for Statistical Computing)

Rosenzweig M L 1968 Net primary productivity of terrestrial communities: prediction from climatological data *Am. Naturalist* **102** 67–74

Russell-Smith J *et al* 2007 Bushfires 'down under': patterns and implications of contemporary Australian landscape burning *Int. J. Wildland Fire* **16** 361–77

Scheiter S, Higgins S I, Beringer J and Hutley L B 2014 Climate change and long-term fire management impacts on Australian savannas *New Phytologist* **205** 1211–26

Spessa A, McBeth B and Prentice C 2005 Relationships among fire frequency, rainfall and vegetation patterns in the wet–dry tropics of northern Australia: an analysis based on NOAA-AVHRR data *Glob. Ecol. Biogeogr.* **14** 439–54

Stephenson N L 1998 Actual evapotranspiration and deficit: biologically meaningful correlates of vegetation distribution across spatial scales *J. Biogeogr.* **25** 855–70

Turner D, Ostendorf B and Lewis M 2012 A comparison of NOAA–AVHRR fire data with three Landsat data sets in arid and semi-arid Australia *Int. J. Remote Sens.* **33** 2657–82

van der Werf G R, Randerson J T, Giglio L, Collatz G J, Mu M, Kasibhatla P S, Morton D C, DeFries R S, Jin Y and van Leeuwen T T 2010 Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009) *Atmos. Chem. Phys.* **10** 11707–35

van Vuuren D *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31

Westerling A L, Turner M G, Smithwick E A H, Romme W H and Ryan M G 2011 Continued warming could transform Greater Yellowstone fire regimes by mid-21st century *Proc. Natl Acad. Sci. USA* **108** 13165–70

Whitman E, Batllori E, Parisien M-A, Miller C, Coop J D, Krawchuk M A, Chong G W and Haire S L 2015 The climate space of fire regimes in north-western North America *J. Biogeogr.* **42** 1736–49

Williams C A *et al* 2012 Climate and vegetation controls on the surface water balance: synthesis of evapotranspiration measured across a global network of flux towers *Water Resour. Res.* **48** W06523

Williams J W and Jackson S T 2007 Novel climates, no-analog communities, and ecological surprises *Frontiers Ecol. Environ.* **5** 475–82

Yang Y, Long D and Shang S 2013 Remote estimation of terrestrial evapotranspiration without using meteorological data *Geophys. Res. Lett.* **40** 3026–30