SUPPORTING INFORMATION

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


*Correspondence to: m.boer@westernsydney.edu.au

Appendix S1. Raw data plots of fire activity index as a function of $E$ and $E_0$ (Figure S1)

Appendix S2. Validation of the climate-fire response surface (Figure S2-3, Table S1)

Appendix S3. Modelling of 0.50 quantile fire activity index (Figure S4-5)

Appendix S4. Mean annual precipitation and potential evapotranspiration for the modelling period (1997-2010) relative to 1986-2005 baseline conditions (Figure S6).

Appendix S5. Fuel composition in domains of PL- or DL-type fire (Figure S7-8)

Appendix S6. Position of key biome types relative to climate-fire response surface (Figure S9).
Figure S1. a) Three-dimensional scatter plot of recorded fire activity index ($F$) against mean annual actual evapotranspiration ($E$) and potential evapotranspiration ($E_0$) for the modelling period 1997-2010. Panels b) and c) are scatter plots of $F$ against $E$ and $E_0$, respectively.
Appendix S2. Validation of the climate-fire response surface

The modelled $F_{0.99}$ response surface (Fig. 1a) was validated against the 50% of the data that was not used for model fitting. To do so the validation data was binned into 50 mm x 50 mm $E, E_0$ bins and the corresponding value of $F_{0.99}$ identified for all bins with a minimum of 100 observations (N=221). Predicted values of $F_{0.99}$ were extracted from the modelled mean response surface using the same set of 221 $E, E_0$ coordinates. A linear model was fitted to the 221 pairs of predicted and observed values of $F_{0.99}$ (Fig. S2), showing that the modelled mean response surface explained a large fraction of the continental variation in $F_{0.99}$ (adj. $R^2$: 0.89, RMSE: 0.09) and model residuals were close to normally distributed.

Figure S2. Predicted versus observed 0.99 quantile values of the fire activity index for 221 validation grid points evenly spread across $E, E_0$ space. The continuous black curve is the linear regression line and the dashed lines indicates the 1:1 relationship.
**Table S1.** Mean and 95% confidence intervals of model coefficients (eq. 2) obtained from 1000 model fits.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Mean</th>
<th>95% CIs</th>
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<tr>
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<tr>
<td>c</td>
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<tr>
<td>d</td>
<td>1.5864</td>
<td>-1.0709, 4.0327</td>
</tr>
</tbody>
</table>

**Figure S3.** Mean annual $E$ and $E_0$ (1986-2005) for grid cells located on the boundary between the domains of PL- and DL-type fire identified in the fire response surface (Fig. 2a).
Appendix S3. Modelling of 0.50 quantile fire activity index

The response surface of the 0.50 quantile fire activity index, $F_{0.50}$, as a function of $E$ and $E_0$, was modelled using a similar approach as for the 0.99 quantile surface. Again we used the random sample of 50% of the data for model fitting and the other 50% was used for validation. The same bootstrap procedure was used as for the modelling of $F_{0.99}$, except this time we fitted a non-parametric model to the sampled data. The smoothing parameter was set heuristically to produce a similar smoothness as for the $F_{0.99}$ model. The bootstrap was run 1000 times to produce 1000 response surfaces from which a mean $F_{0.50}$ response surface was computed (Fig. S4).

Validation of the $F_{0.50}$ response surface followed the same procedure as for the $F_{0.99}$ model (Appendix S2), showing an excellent fit to the data (adj. $R^2$: 0.96, RMSE: 0.03).

Figure S4. Fitted 0.50 quantile surface of the fire activity index (1997-2010) as a function of mean annual actual evapotranspiration ($E$) and potential evapotranspiration ($E_0$).
Figure S5. Predicted versus observed 0.50 quantile values of the fire activity index for 221 validation grid points evenly spread across $E, E_0$ space. The continuous black curve is the linear regression line and the dashed lines indicates the 1:1 relationship.

Figure S6. Absolute differences (in mm y\(^{-1}\)) for mean annual precipitation (a) and Modified Hargreaves potential evapotranspiration (Droogers & Allen, 2002) (b) between the fire-climate modelling period (1997-2010) and the 1986-2005 baseline period. Anomalies are mean annual values for 1997-2010 minus mean annual values for 1986-2005. Mean annual precipitation for 1997-2010 was substantially higher than for 1986-2005 in northern Australia and lower in the southern half of the continent, while mean annual potential evapotranspiration for 1997-2010 was lower than for 1986-2005 in much of the continent, except in coastal regions of the north where it was higher.
Appendix S5. Fuel composition in domains of PL- or DL-type fire

Field observations

Field observations of live and dead fuel loads, and vegetation cover were made at 113 sites across Australia in 2012 and 2013 (Fig. S7). At each site, a 15-m transect was established and 3–5 × 1-m$^2$ quadrats placed along the transect. Within each quadrat, all fine litter (<0.6 mm minimum diameter) and standing grass (live and dead) was clipped and fresh weight recorded in the field. Fuel moisture contents were quantified from oven-dried samples to estimate dry mass of each fuel component. Tree cover was estimated using a spherical densiometer, with a measurement taken at the start and end of the transect. The grass fuel percentage was calculated as dry matter of standing grass over total dry fuel mass times 100.

Figure S7. Locations of field sites used for fuel observations (n=113) (Source: unpublished field data, D.M.J.S. Bowman, B. Murphy and M.A. Cochrane). The background map shows spatial distribution of MODIS tree cover percentage (MOD44B Collection 4 product, version 3, 500 m resolution).
In this study we have modelled mean annual fire activity in Australia as a function of two climatic water balance terms (Stephenson, 1998), mean annual actual evapotranspiration ($E$) and potential evapotranspiration ($E_0$), and used the $E$, $E_0$ direction of the modelled fire activity gradient to distinguish climatic domains of fuel productivity-limited (PL) and fuel dryness-limited (DL) fire. We hypothesized that the sensitivity of fire activity to variation in either $E$ or $E_0$ indicates whether fuels consist predominantly of grasses and herbaceous plants or litter from woody plants.

We used two data sets to analyse the relationship between fuel type and predominant sites across Australia (Fig. S7) and the continental-wide tree cover percentage product (MOD44B, Collection 4) from the Moderate Resolution Imaging Spectroradiometer (MODIS). We showed that tree cover is a strong predictor of the maximum grass fuel percentage (Fig. 2a), so that remotely sensed tree cover can be used to characterise fuel type across the continent.

We first determined the location of our field sites in $E$, $E_0$ space (Fig. 1) using gridded climate data for the 1986-2005 baseline period and the corresponding probability of classification into the domains of PL- or DL-type fire (Fig. 2a). We then analysed whether the observed grass component of the total fuel loads was different for the sites from the domains of PL- and DL-type fire using a Welch two sample t-test (Fig. S7a). The results show a significant difference between the two domains in the ranges and means of grass fuel percentages ($t = 4.2371$, df = 36.519, p-value = 0.000147).

**Figure S7.** a) Grass fuel as percentage of total (dead) fuel load at field sites across Australia (n=113) grouped in two domains, PL-type fire and PL-type fire, according to their long-term
climatic water balance. b) MODIS tree cover percentage for all 0.05° x 0.05° grid cells in Australia for the same fire-climate domains.

The MODIS tree cover percentage data was resampled to the same 0.05° x 0.05° grid used for the climate layers. Then mean annual (1986-2005) $E$ and $E_0$ were used to determine the location of every 0.05° x 0.05° grid cell (n=239,230) in $E$, $E_0$ space, as well as their affinity to the domains of PL- or DL-type fire. We compared tree cover percentages in the two fire regime domains using a Welch two sample t-test (Fig. S7b). As hypothesized, tree cover percentages are significantly lower ($t = -203.32$, $df = 7476.5$, p-value < 2.2e-16) in grid cells from the domain of PL-type fire than in those of the domain of DL-type fire.

The findings of both analyses confirm that fuel type and dominant climatic constraint on fire activity are related. Consistent with current knowledge of fire-climate relations (Bradstock, 2010; Krawchuk & Moritz, 2011), environments in the domain of PL-type fire have low tree cover and fuels of high grass content, while environments in the domain of DL-type fire have high tree cover and fuels with low grass content.
Appendix S6. Position of key biome types relative to climate-fire response surface

**Figure S9.** Position of four key biome types relative to fitted $F_{0.99}$ response surface (Fig. 1a). The grey area indicates the total $E, E_0$ space covered by the Australian data set. The coloured zones refer to ‘fire regime niches’ proposed by Murphy et al. (2013): arid/semi-arid hummock grassland (FRN8), arid/semi-arid Acacia woodland (FRN4), temperate tall Eucalypt forest (FRN16), and tropical rainforest (FRN3).
References


