

# Improved simulation of fire-vegetation interactions in the Land surface Processes and eXchanges Dynamic Global Vegetation Model (LPX-Mv1)

D. I. Kelley<sup>1</sup>, S. P. Harrison<sup>1,2</sup>, and I. C. Prentice<sup>1,3</sup>

<sup>1</sup>Department of Biological Sciences, Macquarie University, North Ryde, NSW 2109, Australia

<sup>2</sup>Geography & Environmental Sciences, School of Archaeology, Geography and Environmental Sciences (SAGES), University of Reading, Whiteknights, Reading, RG6 6AB, UK

<sup>3</sup>AXA Chair of Biosphere and Climate Impacts, Grantham Institute for Climate Change and Department of Life Sciences, Imperial College, Silwood Park Campus, Ascot SL5 7PY, UK

*Correspondence to:* D. I. Kelley (douglas.kelley@students.mq.edu.au)

**Abstract.** The Land surface Processes and eXchanges (LPX) model is a fire-enabled dynamic global vegetation model that performs well globally but has problems representing fire regimes and vegetative mix in savannas. Here we focus on improving the fire module. To improve the representation of ignitions, we introduced a treatment of lightning that allows the fraction of ground strikes to vary spatially and seasonally, realistically partitions strike distribution between wet and dry days, and varies the number of dry-days with strikes. Fuel availability and moisture content were improved by implementing decomposition rates specific to individual plant functional types and litter classes, and litter drying rates driven by atmospheric water content. To improve water extraction by grasses, we use realistic plant-specific treatments of deep roots. To improve fire responses, we introduced adaptive bark thickness and post-fire resprouting for tropical and temperate broadleaf trees. All improvements are based on extensive analyses of relevant observational data sets. We test model performance for Australia, first evaluating parameterisations separately and then measuring overall behaviour against standard benchmarks. Changes to the lightning parameterisation produce a more realistic simulation of fires in southeastern and central Australia. Implementation of PFT-specific decomposition rates enhances performance in central Australia. Changes in fuel drying improve fire in northern Australia, while changes in rooting depth produce a more realistic simulation of fuel availability and structure in central and northern Australia. The introduction of adaptive bark thickness and resprouting produces more realistic fire regimes in Australian savannas. We also show that the model simulates biomass recovery rates consistent with observations from several different regions of the world characterized by resprouting vegetation. The new model (LPX-Mv1) produces an improved simulation of observed vegetation composition and mean annual burnt area, by 33%

and 18% respectively compared to LPX.

## 1 Introduction

The Land surface Processes and eXchanges (LPX) dynamic global vegetation model (DGVM) incorporates fire through a coupled fire module (Prentice et al., 2011) as fire is a major agent in vegetation disturbance regimes (Bond and Van Wilgen, 1996) and contributes to changes in interannual atmospheric carbon fluxes (Prentice et al., 2011; van der Werf et al., 2008). In common with several other fire models (e.g. Arora and Boer, 2005; Kloster et al., 2010; Thonicke et al., 2010; Li et al., 2012; Prentice et al., 2011; Pfeiffer et al., 2013) LPX explicitly simulates lightning ignitions, fuel load, susceptibility to burning, fire spread and fire-induced mortality. However, it does not consider anthropogenic ignitions because the dependencies of such ignition with population density, used as a basis for such ignitions in other models, have been shown to be unrealistic (Prentice et al., 2011; Bistinas et al., 2014). LPX realistically simulates fire and vegetation cover globally but performs relatively poorly in grassland and savanna ecosystems (Kelley et al., 2013) – areas where fire is particularly important for maintaining vegetation diversity and ecosystem structure (e.g. Williams et al., 2002; Lehmann et al., 2008; Biganzoli et al., 2009). Specifically:

- LPX produces sharp boundaries between areas of high burning and no burning in tropical and temperate regions. These sharp fire boundaries produce sharp boundaries between grasslands and closed-canopy forests. The unrealistically high fire-induced tree mortality prevents the development of vegetation characterized by varying mixtures of tree and grass plant functional types (PFTs) that are characteristic of more open forests, savannas and woodlands.
- LPX simulates too little fire in areas of high but seasonal rainfall because fuel takes an unrealistically long time to dry, and because LPX fails to produce open woody vegetation in these areas.
- In arid areas, where fire is limited by fuel availability, LPX simulates too much Net Primary Production (NPP) resulting in unrealistically high fuel loads and generating more fire than observed.

To address these shortcomings in the version of LPX running at Macquarie University (here designated LPX-M), we re-parameterised lightning ignitions, fuel moisture, fuel decomposition, plant adaptations to arid conditions via rooting depth, and woody plant resistance to fire through bark thickness. In each case, the new parameterisation was developed based on extensive data analysis. We tested each parameterisation separately, and then all parameterisations combined, using a comprehensive benchmarking system (Kelley et al., 2013) which assesses model performance against observations of key vegetation and fire processes. We then included a new treatment of woody plant recovery after fire through resprouting – a behavioural trait that increases post-fire

competitiveness compared to non-resprouters in fire-prone areas (Clarke et al., 2013) – and tested the impact of introducing this new component on model performance. In this paper, we begin by describing the basic fire parameterisations in LPX (Section 2) and then go on to explain how these parameterisations were changed in LPX-Mv1 (Section 3) before evaluating whether these new data-derived parameterisations improve the simulation of vegetation patterns and fire regimes (Section 4).

## 2 LPX model description

LPX is a Plant Functional Type (PFT) based model. Nine PFTs are distinguished by a combination of life form (tree, grass) and leaf type (broad, needle), phenology (evergreen, deciduous) and climate range (tropical, temperate, boreal) for trees and photosynthetic pathway ( $C_3$ ,  $C_4$ ) for grasses. PFTs are represented by a set of parameters. Each PFT that occurs within a gridcell is represented by an “average” plant, and ecosystem-level behaviour is calculated by multiplying the simulated properties of this average plant by the simulated number of individuals in the PFT in that gridcell. PFT-specific properties (e.g. establishment, mortality and growth) are updated annually, but water and carbon-exchange processes are simulated on shorter timesteps.

LPX incorporates a process-based fire scheme (Fig. 1) run on a daily timestep (Prentice et al., 2011). The LPX fire scheme is modified from the Spread and Ignitions FIRE model (SPITFIRE: Thonicke et al., 2010). In this Section, we describe those aspects of the LPX fire model that appear to contribute to poor simulation of fire regimes in Australia (and likely other semi-arid regions) and which we have re-examined and re-parameterised on the basis of data analyses (see Section 3). Ignition rates are derived from a monthly lightning climatology, interpolated to the daily timestep. The number of lightning strikes that reach the ground (cloud-to-ground: CG) is specified as 20 % of the total number of strikes (Thonicke et al., 2010). The CG lightning is split into dry ( $CG_{dry}$ ) and wet strikes based on the fraction of wetdays in the month ( $P_{wet}$ ):

$$CG_{dry} = CG \cdot (1 - P_{wet}^{\beta}) \quad (1)$$

where  $\beta$  is a parameter tuned to 0.00001. “Wet” lightning is not considered to be an ignition source (Prentice et al., 2011). Lightning is finally scaled down by 85 % to allow for discontinuous current strikes. Numerical precision limits of the compiled code means the function described by Eq. (1) effectively removes all strikes in months with more than two wet days in LPX. Monthly “dry” lightning is distributed evenly across all dry days.

Fuel loads are generated from litter production and decay using the vegetation dynamics algorithms in LPJ (Sitch et al., 2003). LPX does not simulate competition between  $C_3$  and  $C_4$  grasses explicitly; in gridcells where  $C_3$  and  $C_4$  grasses co-exist, the total NPP is estimated as the potential NPP of each grass type in the absence of the other type and this produces erroneously high NPP. This problem can be corrected by scaling the fractional projective cover (FPC) and Leaf Area Index (LAI) of each

grass PFT by the ratio of total simulated grass leaf mass of both PFTs to the leaf mass expected if only one grass PFT was present (B. Stocker, personal communication, 2012). This was done in LPX-Mv1.

95 Fuel decomposition rate ( $k$ ) depends on temperature and moisture, and is the same for all PFTs and fuel structure types:

$$k = k_{10} \cdot g(T) \cdot f(w) \quad (2)$$

where  $k_{10}$  is a decomposition rate at a reference temperature of 10 °C, set to 35 % each year;  $g(T)$  describes the response to monthly mean soil temperature ( $T_{\text{soil, m}}$ ) described by Lloyd and Taylor (1994):

$$g(T) = \begin{cases} e^{308.56 \cdot \left( \frac{1}{56.02} - \frac{1}{T_{\text{soil, m}} + 46.02} \right)}, & \text{if } T_{\text{soil, m}} \geq -40 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

and  $f(w)$  is the moisture response to the top layer soil water content ( $w$ ) described by Foley (1995)

$$105 \quad f(w) = 0.25 + 0.75 \cdot w \quad (4)$$

where  $w$  is in fractional water content.

The litter is allocated to four fuel categories based on litter size as described by Thonicke et al. (2010):

- 110 – *1 h fuel* – which represents leaves and small twigs, is the leaf and herb mass plus 4.5 % of the litter that comes from tree heart- and sapwood;
- *10 h fuel* – representing small branches, is 7.5 % of the litter from heart- and sapwood
- *100 h fuel* – large branches, is 21 % of the litter that comes from heart- and sapwood
- *1000 h fuel* – boles and trunks, is the remaining 67 % of the litter that comes from heart- and
- 115 sapwood.

The hour designation represents the decay rate of fuel moisture, and is equal to the amount of time for the moisture of the fuel to become  $(1 - 1/\exp) = 63\%$  closer to the moisture of its surroundings (Albini, 1976; Anderson et al., 1982).

In LPX, litter drying rate is described by the cumulative Nesterov Fire Danger Index (NI: Nesterov, 1949) as described by Running (1987), and a fuel-specific drying rate parameter ( $\alpha_{\text{xhr}}$ : Venevsky et al., 2002) which was tuned to provide the best results against fire observations (Thonicke et al., 2010). NI is cumulated for each consecutive day with rainfall  $\leq 3$  mm, and is calculated using maximum daily temperature ( $T_{\text{max}}$ ) and an approximation of dew point:

$$125 \quad T_{\text{dew}} = T_{\text{min}} - 4 \quad (5)$$

where  $T_{\min}$  is the daily minimum temperature and both  $T_{\min}$  and  $T_{\max}$  are in °C.

Daily precipitation is simulated based on monthly precipitation and fractional wet days using a simple weather generator (Gerten et al., 2004), and the diurnal temperature range is calculated from daily maximum and minimum temperature interpolated from monthly data.

130 Fire spread, intensity and residence time are based on weather conditions and fuel moisture, and calculated using the Rothermel equations (Rothermel, 1972). Fire intensity and residence time influence fire mortality via crown scorching and cambial damage.

The amount of cambial damage is determined by fire intensity and residence time in relation to bark thickness, with thicker bark offering protection for longer fire residence times. Bark thickness  
135 (BT) is calculated as a linear function of tree diameter at breast height (DBH), with specific slope and intercept values for each PFT:

$$BT = a + b \cdot DBH \quad (6)$$

The values of  $a$  and  $b$  can be found in Thonicke et al. (2010).

140 The probability of mortality from cambial damage ( $P_m$ ) is calculated from the fire residence time ( $\tau_l$ ) and a critical time till cambial damage ( $\tau_c$ ) based on bark thickness:

$$P_m(\tau) = \begin{cases} 0, & \text{if } \frac{\tau_l}{\tau_c} \leq 0.22 \\ 0.563 \cdot \frac{\tau_l}{\tau_c} - 0.125, & \text{if } 0.22 \leq \frac{\tau_l}{\tau_c} \leq 2 \\ 1, & \text{if } \frac{\tau_l}{\tau_c} \geq 2 \end{cases} \quad (7)$$

and

$$145 \quad \tau_c = 2.9 \cdot BT^2 \quad (8)$$

where  $\tau$  is the ratio  $\tau_l/\tau_c$ . Both  $\tau_l$  and  $\tau_c$  are in minutes and BT is in cm.

LPX uses a two-layer soil model. The water content of the upper (50 cm) layer is the difference between through-fall (precipitation–interception) and evapotranspiration (ET), runoff and percolation  
150 to the lower soil layer. Water content in the lower 1 m layer is the difference between percolation from the upper layer, transpiration from deep roots and runoff (Gerten et al., 2004). The upper soil layer responds more rapidly to changes in inputs, whereas the water content of the lower soil layer is generally more stable. The fraction of roots in each soil layer is a PFT-specific parameter.

### 3 Changes to the LPX-M fire module

155 Improvements to the LPX-M fire module focussed on re-parameterisation of lightning ignitions, fuel drying rate, fuel decomposition rate, rooting depth, and the introduction of adaptive bark thickness

and of resprouting. The improvements are based on analyses of large-scale regional and/or global data sets, and are therefore generic. Although we focus on Australia for model evaluation, we have made no attempt to tune the new parameterisations using Australian observations.

### 160 3.1 Lightning ignitions

Regional studies have shown that the CG proportion of total lightning strikes varies between 0.1–50 % of total strikes. This variability has been related to latitude (Price and Rind, 1993; Pierce, 1970; Prentice and Mackerras, 1977), storm size (Kuleshov and Jayaratne, 2004), total flash count (Boccippio et al., 2001), and topography (Boccippio et al., 2001; de Souza et al., 2009). We  
165 compared the remotely-sensed flash counts of total flash counts (i.e. Inter-Cloud, or IC, plus CG) from the Lightning Imaging Sensor (LIS – Christian et al., 1999; Christian, 1999, <http://grip.nsstc.nasa.gov/>) with the National Lightning Detection Network Database (NLDN) records of lightning ground-strikes (CG) for the contiguous United States (available at <http://thunderstorm.vaisala.com/>; Cummins and Murphy, 2009), for each month in 2005 at the 0.5° resolution of LPX. These analyses  
170 were confined to south of 35° N, a limitation imposed by satellite coverage of the total strikes (Christian et al., 1999).

LIS observed each cell for roughly 90 s each overpass with 11–21 overpasses each month depending on latitude (Christian et al., 1999), and therefore only represents a sample of the total lightning. Overpasses for each 0.5° cell have a time stamp for the start and end of each overpass, along  
175 with detection efficiency and total observation time, which allows for observational blackouts. We scaled the flash count from each overpass for detection efficiency and the ratio of observed to total overpass time. These scaled flash counts were summed for each month, to give monthly recorded total lightning RL, which includes both cloud to cloud and cloud to ground strikes (i.e. IC + CG).

NLDN registered each ground lightning strike separately with a time stamp accurate to 1/1000th  
180 of a second, which allowed us to calculate the number of ground-registered NLDN strikes for each LIS overpass. This number of ground strikes was then scaled for a universal detection efficiency of 90 % (Boccippio et al., 2001; Cummins and Murphy, 2009), and summed up for the month, to give monthly recorded CG strikes (RG). The CG fraction was taken as RG/RL. Total flash count ( $L$ ) was calculated by scaling the total ground registered lightning for each month by the CG fraction.  
185 The relationship between fractional CG and total lightning was determined using non-linear least squares regression, testing for both power and exponential functions. The best (Fig. 2a) was given by:

$$CG = L \cdot \min(1, 0.0408 \cdot L^{-0.4180}) \quad (9)$$

190 where  $L$  is in flash/km<sup>2</sup>/day. We also tested topography and topographic complexity, calculated from topographic data from WORLDCLIM (Hijmans et al., 2005). These variables were not significantly related to the observed CG fraction, and so we have not included them as predictors

in the new parameterisation.

We examined the relationship between CG strikes and the daily distribution of precipitation using the Climate Prediction Center (CPC) US Unified Precipitation data (Higgins and Centre, 2000; Higgins et al., 1996) provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (<http://www.esrl.noaa.gov/psd/>). Days are classified as dry if there was zero precipitation. We used data for every month of 2005, this time covering the whole of the contiguous United States. We used Generalised Linear Modelling (GLM; Hastie and Pregibon, 1992) to compare  $CG_{dry}$  to  $P_{wet}$  and monthly precipitation from CPC and the Climate Research Unit (CRU) TS3.1 data set (Harris et al., 2013), as well as temperature from CRU TS3.1 (Harris et al., 2013).  $P_{wet}$  from both CPC and CRU were the best and only significant predictors. Using CPC for consistency, the best relationship for  $CG_{dry}$  (Fig. 2b) was:

$$CG_{dry} = 0.85033 \cdot CG \cdot e^{-2.835 \cdot P_{wet}} \quad (10)$$

where  $CG_{dry}$  is the number of strikes on days with zero precipitation, and  $P_{wet}$  is the amount of precipitation on days with rain. We determined a new parameter for the fraction of dry days with lightning strikes (“dry storm days”) by comparing the fraction of dry days in CPC when lightning occurred ( $P_{dry, lightn}$ ) with  $CG_{dry}$  calculated in Eq. (10) (Fig. 2c). The analysis was performed using the same spatial domain as the analysis of  $CG_{dry}$ . The best relationship with the least squared residuals (Fig. 2c) was:

$$P_{dry, lightn} = 1 - \frac{1}{1.099 \cdot (CG_{dry} + 1)^{94.678.69}} \quad (11)$$

The results of these analyses were used in the new parameterisation of lightning in LPX-Mv1. IC lightning was removed by applying Eq. (9), where  $L$  is taken from the monthly lightning climatology inputs. Wet lightning was removed from the remaining CG strikes by applying Eq. (10). A sensitivity test including lightning on wet days shows that such ignitions have little impact or degrade the simulation of burnt area (see Supplement). The remaining  $CG_{dry}$  was distributed evenly onto the number of dry days defined by Eq. (11). The dry lightning days were selected randomly from the days without precipitation as determined by the weather generator (Gerten et al., 2004). Polarity affects the duration of lightning pulses, with negative polarity more likely to produce discontinuous pulses that are insufficient to raise the temperature to ignition point. This discontinuous current lightning was removed at the same constant rate as in LPX because there are no data sets that would allow analyses on which to base a re-parameterisation.

Pfeiffer et al. (2013) have argued that inter-annual variability in lightning is important, especially in high latitude regions with relatively few fires, and have introduced this in a version of LPJ (LPJ-LMfire v1.0) based on a scaling with convective available potential energy (CAPE). This idea was adopted from Peterson et al. (2010) who demonstrated that the probability of lightning occurring on a dry day varies inter-annually with CAPE. However, LPJ-LMfire (v1.0) does not

230 contain a treatment of dry lightning nor “storm days”, so the approach taken there is parallel to ours. Murray et al. (2012) have shown that interannual variability in total flash count (i.e standard deviation of IC + CG) is < 10 % in tropical and temperate regions. This, and the fact that the LIS data set only covers a period of 10 yr and it is not obvious how to extrapolate lightning under a changing climate, means that we have retained the use of a lightning climatology for total lightning in LPX-Mv1, but  
 235 with seasonally and inter-annually varying treatments of dry lightning and dry storm days.

### 3.2 Fuel drying

The formulation of fuel drying in LPX results in drying times that are too slow in most tropical and temperate regions. Under stable and dry weather conditions with a  $T_{\max}$  of 30 °C and  $T_{\text{dew}}$  of 0 °C, for example, 1 h fuel in LPX would take 25 h to lose 63 % of its moisture, 10 h fuel would  
 240 take roughly 20 days, 100 h fuel takes 2 months, and 1000 h fuel takes 3 yr. The approximation of  $T_{\text{dew}}$  used in LPX has been shown to be too high in arid and semi-arid areas, and during dry periods in seasonal climates (Friend, 1998; Running, 1987), which also contributes to slower-than-expected drying. Additionally, given that the moisture content is calculated cumulatively, a sequence of days with < 3 mm of rain could result in complete drying of fuel, no matter what the moisture content of  
 245 the air.

In order to improve this formulation, we replace the description of fuel moisture content in LPX with one based on the moisture content of the air. As fuel types are distinguished by the time it takes for fuel to come into equilibrium with the surroundings, this new formulation is consistent with the definition of fuel types. Fuel moisture decays towards an “equilibrium moisture content” ( $m_{\text{eq}}$ ) at  
 250 a rate that matches the definition of the fuel class (i.e, 1 h fuel takes 1/24th of a day to become 63 % closer to  $m_{\text{eq}}$ ):

$$m_{x,d} = \frac{m_{\text{eq}}}{100} + \left( m_{x,d-1} - \frac{m_{\text{eq}}}{100} \right) \cdot e^{-24/x} \quad (12)$$

where  $m_{x,d}$  is the daily moisture content of fuel size in each drying-time class ( $x$ ) with a moisture  
 255 decay rate of  $24/x$ ; and  $m_{x,d-1}$  is the moisture content on the previous day.

There are several choices of fuel equilibrium models that could be used for  $m_{\text{eq}}$ , with variation in the magnitude of the  $m_{\text{eq}}$  response to relative humidity ( $H_R$ ), particularly at extremes (i.e  $H_R \rightarrow 0$ , 100 %), and the potential for opposite responses to temperature depending on weather conditions (Sharples et al., 2009; Viney, 1991). Viney (1991) attributed this variation to the choice of fuel type  
 260 for which each model was calibrated. We chose the model described by Van Wagner and Pickett (1985) for  $m_{\text{eq}}$  as it has been calibrated against multiple fuel types (Van Wagner, 1972) and is



designed to be more accurate at both high and low  $H_R$  (Sharples et al., 2009; Viney, 1991):

$$m_{eq} = \begin{cases} m_{eq,1} + m_{eq,2} + m_{eq,3}, & \text{if } Pr_d \leq 3 \text{ mm} \\ 100, & \text{otherwise} \end{cases} \quad (13)$$

265 where

$$m_{eq,1} = 0.942 \cdot (H_R^{0.679}) \quad (14)$$

$$m_{eq,2} = 0.000499 \cdot e^{0.1 \cdot H_R} \quad (15)$$

$$m_{eq,3} = 0.18 \cdot (21.1 - T_{max}) \cdot (1 - e^{-0.115 \cdot H_R}) \quad (16)$$

270  $H_R$  is calculated using the August–Roche–Magnus approximation (Lawrence, 2005), which has been shown to be accurate for  $T_{dew}$  of between 0 and 50 °C and  $T_{max}$  between 0 and 60 °C (Lawrence, 2005):

$$H_R = 100 \cdot \frac{e^{17.271 \cdot T_{dew} / (237.7 + T_{dew})}}{e^{17.271 \cdot T_{max} / (237.7 + T_{max})}} \quad (17)$$

275 We use a new formulation for  $T_{dew}$  derived from information from 20 weather stations across the United States (Kimball et al., 1997):

$$T_{dew,k} = T_{min,k} \cdot (-0.127 + 1.121 \cdot W_{EF} + 0.0006 \cdot \Delta T) \quad (18)$$

where  $T_{dew,k}$  is the daily dew point temperature in Kelvin;  $\Delta T$  is the difference between daily  $T_{max}$

280 and  $T_{min}$ , and  $W_{EF}$  is given by:

$$W_{EF} = (1.003 - 1.444 \cdot EF + 12.312 \cdot EF^2 - 32.766 \cdot EF^3) \quad (19)$$

and EF is the ratio of daily potential evapotranspiration ( $PET_d$ ) – calculated as described in Gerten et al. (2004) – and annual precipitation ( $Pr_a$ ):

$$285 \quad EF = PET_d / Pr_a \quad (20)$$

Kimball et al. (1997) showed that this approximation of  $T_{dew}$  improved the correlation with  $T_{dew}$  measurements by 20 % when tested against 32 independent weather stations, with  $T_{dew}$  showing differences up to 20 °C in semi-arid and arid climates. The more conventional assumption that

290  $T_{dew} = T_{min} - 4$  would thus result in higher dew-point temperatures and slower fuel-drying rates. Although we have replaced the formulation of fuel-drying rate, including the formulation of  $T_{dew}$ , we continue to use the NI to describe the likelihood of an ignition starting a fire in LPX-Mv1.

### 3.3 Fuel decomposition

Fuel decomposition rates vary with the size and type of material (Cornwell et al., 2008, 2009;

295 Weedon et al., 2009; Chave et al., 2009). Brovkin et al. (2012) analysed decomposition rates derived

from the TRY plant trait database (Kattge et al., 2011, <http://www.try-db.org/TryWeb/About.php>) and showed that there was an order of magnitude difference in the decomposition rates of wood and leaf/grass litter. Thus, grass decomposes at an average rate of 94 % per year, while wood decomposes at a rate of 5.7 % per year. The rate of both leaf and wood decomposition varies between PFTs to a lesser extent than between wood and grass, although the variation is still significant (Brovkin et al., 2012), with leaf decomposition ranging between 76 % and 120 %, and wood between 3.9 % and 10.4 % per year (Table 1). Brovkin et al. (2012) also showed that the decomposition rates of woody material are not moisture dependent.

We have implemented the PFT-specific relationships found by Brovkin et al. (2012), for woody ( $k_{10, \text{wood}}$  for 10–1000 h fuel – see Table 1) and leaf ( $k_{10, \text{leaf}}$  for 1 h fuel – see Table 1) litters. We use a relationship between decomposition and temperature for woody fuel that removes the soil moisture dependence in LPX:

$$k_{\text{wood}} = k_{10, \text{wood}} \cdot Q_{10}^{(T_{m, \text{soil}} - 10)/10} \quad (21)$$

$Q_{10}$  is the PFT-specific temperature response of wood decomposition described in Table 1 and  $k_{10, \text{wood}}$  is the decomposition rate at a reference temperature of 10 °C. Leaf decomposition still follows Eq. (2).

### 3.4 Rooting depth

There are inconsistencies in the values used in LPX-M for the fraction of deep roots specified for each PFT. For example, the fraction of deep roots specified for  $C_4$  grasses (20 %) is greater than the fraction specified for tropical broadleaf evergreen trees (15 %), even though trees have deeper roots than grasses (Schenk and Jackson, 2005). Additionally, benchmarking against arid grassland and desert litter production shows that simulated fine litter production is roughly 250% greater than observations. Having a high proportion of deep roots allows plants to survive more arid conditions, thanks to a more stable water supply in deep soil.

We re-examined the PFT-specific values assigned to rooting fraction using site-based data for the cumulative rooting fraction depth from Schenk and Jackson (2002a,b, 2005). In the original publications, life form, leaf type, leaf phenology and the cause of leaf fall (i.e. cold or drought) were recorded for each site. This allowed us to classify sites into LPX PFTs as shown in Table 2. The original data source does not distinguish different types of grassland. We therefore separated these sites into warm ( $C_4$  dominated) and cool ( $C_3$  dominated) grasslands depending on their location and climate. Sites were allocated to warm grassland if they occurred in locations where the mean temperature of the coldest month (MTCO) was  $> 15.5$  °C and to cool grasslands where MTCO was  $\leq 15.5$  °C as in Harrison et al. (2010). MTCO for each site was based on average conditions for 1970–2000 derived from the CRU TS3.1 data set (Harris et al., 2013).

The rooting-depth dataset gives the cumulative fraction depth of 50 % ( $D_{50}$ ) and 95 % ( $D_{95}$ ) of

the roots at a site. These were used to calculate the cumulative root fraction at 50 cm (i.e the fraction in the upper soil layer):

$$R_{50\text{ cm}} = 1 / (1 + (0.5 / D_{50}^c)) \quad (22)$$

where

$$c = \frac{\log 0.5 / 0.95}{\log D_{95} / D_{50}} \quad (23)$$

We derived Eqs. (22) and (23) by re-arranging Eq. (1) in Schenk and Jackson (2002b).

The PFT-specific (Fig. 3) fraction of deep roots ( $DR_{\text{pft}}$ ) is then implemented as:

$$DR_{\text{pft}} = 1 - \text{mean}(R_{50\text{ cm}, \text{pft}}) \quad (24)$$

See Table 1 for new parameter values.

### 3.5 Bark thickness

There is considerable variability in bark thickness between different tree species (Halliwell and Apps, 1997; Fyllas and Patino, 2009; Paine et al., 2010), such that it is unrealistic to prescribe a single constant value for the relationship between bark thickness and stem diameter within a PFT. Furthermore, bark thickness within related species appears to vary as a function of environmental conditions, and most particularly with fire frequency (Brando et al., 2012; Climent et al., 2004; Cochrane, 2003; Lawes et al., 2011a). Thus, at an ecosystem-level, bark thickness is an adaptive trait.

We assess the relationship between bark thickness and stem diameter based on 13297 measurements from 1364 species (see Supplement for information on the studies these were obtained from). The species were classified into PFTs based on their leaf type, phenology and climate range (Table S1); in cases where this was not provided by the original data contributors, we used information from trait databases, floras and the literature (e.g Kauffman, 1991; Greene et al., 1999; Bellingham and Sparrow, 2000; Williams, 2000; Bond and Midgley, 2001; Del Tredici, 2001; Pausas et al., 2004; Paula et al., 2009; Lunt et al., 2011). The climate range was based on the overall range of the species, not derived from the climate of the sites.

For each PFT, we calculated the best fit and the 5–95 % range (Koenker, 2013, Fig. 4) using the simple linear relationship:

$$BT_i = \text{par}_i \cdot \text{DBH} \quad (25)$$

where  $i$  is either: best fit (mid); 5 % (lower); 95 % (upper) ranges. Values for  $\text{par}_i$  are given in Table 1.

We define a probability distribution of bark thicknesses for each PFT, using a triangular relationship

defined by the 5 and 95 % limits of the observations (Fig. 4):

$$T(\text{BT}) = \begin{cases} 0, & \text{if } \text{BT} \leq \text{BT}_{\text{lower}} \\ T_1(\text{BT}), & \text{if } \text{BT}_{\text{lower}} \leq \text{BT} \leq \text{BT}_{\text{mid}} \\ T_2(\text{BT}), & \text{if } \text{BT}_{\text{mid}} \leq \text{BT} \leq \text{BT}_{\text{upper}} \\ 0, & \text{if } \text{BT} \geq \text{BT}_{\text{upper}} \end{cases} \quad (26)$$

370 where  $\text{BT}_{\text{lower}}/\text{BT}_{\text{upper}}/\text{BT}_{\text{mid}}$  is the upper/lower/mid range of BT for a given DBH, calculated using Eq. (25), with  $\text{par}_i$  values in Table 1; and

$$T_1(\text{BT}) = \frac{2 \cdot (\text{BT} - \text{BT}_{\text{lower}})}{(\text{BT}_{\text{upper}} - \text{BT}_{\text{lower}}) \cdot (\text{BT}_{\text{mid}} - \text{BT}_{\text{lower}})} \quad (27)$$

$$T_2(\text{BT}) = \frac{2 \cdot (\text{BT}_{\text{upper}} - \text{BT})}{(\text{BT}_{\text{upper}} - \text{BT}_{\text{lower}}) \cdot (\text{BT}_{\text{lower}} - \text{BT}_{\text{mid}})} \quad (28)$$

375 The distribution is initialized using  $\text{par}_i$  values in Table 1.  $\text{par}_{\text{lower}}$  and  $\text{par}_{\text{upper}}$  remain unchanged from the initial value (Table 1).  $\text{par}_{\text{mid}}$  changes after a fire event, based on the bark thickness of surviving plants. It will also change with establishment, when the post-establishment value represents the wighted average of the bark thickness of new and existing plants (Fig. 5).

The average bark thickness of trees surviving fire is dependent on the current state of  $T(\text{BT})$  and  
380  $P_m$  given in Eq. (7), and is calculated by solving the following integrals:

$$\text{BT}_{\text{mean}} = \frac{N_* \cdot \int_{\text{BT}_{\text{lower}}}^{\text{BT}_{\text{upper}}} \text{BT} \cdot (1 - P_m(\tau)) \cdot T(\text{BT}) d\text{BT}}{N} \quad (29)$$

where  $N_*$  is the number of individuals before the fire event and  $N$  the number of individuals that survive the fire, given by:

$$385 \quad N = N_* \cdot \int_{\text{BT}_{\text{lower}}}^{\text{BT}_{\text{upper}}} (1 - P_m(\tau)) \cdot T(\text{BT}) d\text{BT}. \quad (30)$$

where  $\tau$  is the ratio  $\tau_1/\tau_c$ .

A new mid point of the distribution,  $\text{BT}_{\text{mid}}$ , is calculated from  $\text{BT}_{\text{mean}}$ :

$$390 \quad \text{BT}_{\text{mid}} = 3 \cdot \text{BT}_{\text{mean}} - \text{BT}_{\text{lower}} - \text{BT}_{\text{upper}} \quad (31)$$

The updated  $\text{par}_{\text{mid}}$  value is calculated from the fractional distance between  $\text{BT}_{\text{mid}}$  before the fire event ( $\text{BT}_{\text{mid}}^*$ ), and  $\text{BT}_{\text{upper}}$ :

$$\text{par}_{\text{mid}} = \text{par}_{\text{mid}}^* + \text{BT}_{\text{mid,frac}} \cdot (p_{\text{upper}} - p_{\text{mid}}^*) \quad (32)$$

395 where  $p_{\text{mid}}^*$  was  $p_{\text{mid}}$  before the fire event and

$$\text{BT}_{\text{mid, frac}} = \frac{\text{BT}_{\text{mid}} - \text{BT}_{\text{mid}}^*}{\text{BT}_{\text{upper}} - \text{BT}_{\text{mid,0}}^*} \quad (33)$$

Newly-established plants have a bark thickness distribution ( $E(\text{BT})$ ) described by Eq. (26) based on the initial  $p_{\text{mid}0}$  given in Table 1. Post-establishment  $\text{BT}_{\text{mean}}$  is calculated as the average of  
400 pre-establishment  $T(\text{BT})$  and  $E(\text{BT})$ , weighted by the number of newly established ( $m$ ) and old individuals ( $n$ ):

$$\text{BT}_{\text{mean}} = \frac{\int_{\text{BT}_{\text{lower}}}^{\text{BT}_{\text{upper}}} \text{BT} \cdot (n \cdot T(\text{BT}) + m \cdot E(\text{BT})) d\text{BT}}{n + m} \quad (34)$$

The new  $\text{par}_{\text{mid}}$  is calculated again using Eqs. (31) and (32). In cases where no trees survive fire,  
405  $T(\text{BT})$  is set to its initial value when the PFT re-establishes.

### 3.6 Resprouting

Many species have the ability to resprout from below-ground or above-ground meristems after fire (Clarke et al., 2013). Resprouting ensures rapid recovery of leaf mass, and thus conveys a competitive advantage over non-resprouting species which have to regenerate from seed. Post-fire recovery in  
410 ecosystems that include resprouting trees is fast, with ca 50 % of leaf mass being recovered within a year and full recovery within ca 5–7 yr (Viedma et al., 1997; Calvo et al., 2003; Casady, 2008; Casady et al., 2009; Gouveia et al., 2010; van Leeuwen et al., 2010; Gharun et al., 2013, see Fig. 7 and Table S3).

However, species that resprout from aerial tissue (apical or epicormic resprouters in the terminology  
415 of Clarke et al., 2013) either need to have thick bark (see e.g. Midgley et al., 2011) or some other morphological adaptation to protect the meristem (e.g. see Lawes et al., 2011a,b). Investment in resprouting appears to be at the cost of seed production: in general, resprouting trees produce much less seed and therefore have a lower rate of post-disturbance establishment than non-resprouters (Midgley et al., 2010).

420 Aerial resprouting is found in both tropical and temperate trees, regardless of phenology (Kaufmann and Hartmann, 1991; Bellingham and Sparrow, 2000; Williams, 2000; Bond and Midgley, 2001; Del Tredici, 2001; Paula et al., 2009). It is very uncommon in gymnosperms (Del Tredici, 2001; Paula et al., 2009; Lunt et al., 2011) and does not seem to be promoted by fire in deciduous broadleaf trees in boreal climates (Greene et al., 1999). We therefore introduced resprouting variants of four PFTs  
425 in LPX-Mv1: tropical broadleaf evergreen tree (TBE), tropical broadleaf deciduous tree (TBD), temperate broadleaf evergreen tree (tBE), and temperate broadleaf deciduous tree (tBD). Parameter values were assigned to be the same as for the non-resprouting variant of each PFT, except for BT and establishment rate.

The species used in the bark thickness analysis were categorised into aerial resprouters, other  
430 resprouters and non-resprouters (see Table S1) based on field observations by the original data  
contributors, trait databases (e.g. <http://www.landmanager.org.au>; Kattge et al., 2011; Paula et al.,  
2009) or information in the literature (e.g. Harrison et al., 2014; Malanson and Westman, 1985;  
Pausas, 1997; Dagit, 2002; Tapias et al., 2004; Keeley, 2006).

Resprouting is facultative, and whether it is observed in a given species at a given site may depend  
435 on the fire regime and fire history of that site. Any species that was observed to resprout in one  
location was assumed to be capable of resprouting, even if it was classified as a non-resprouter  
in some studies. The range of BT for each resprouting (RS) PFT was calculated as in Sect. 3.5  
(see Fig. 4 and Table 1). The range of BT was also re-assigned for their non-resprouting (NR)  
counterparts using species classified as having no resprouting ability.

440 The BT and post-fire mortality of RS PFTs is calculated in the same way as for NR PFTs.  
The allocation of fire-killed material in RS PFTs to fuel classes is also the same as for NR PFTs.  
However, after fire events, the RS PFTs are not killed, as described in Eq. (7), but allowed to resprout.  
The new average plant for RS PFTs is calculated as the average of trees not affected by fire and  
fire-affected trees RS trees.

445 Seeding recruitment after disturbance is contingent on many environmental factors. Few studies  
have compared post-disturbance seedling recruitment by resprouters and non-resprouters, and there  
is no standardized reporting of environmental conditions or responses in those studies that do exist.  
However, most studies show that post-disturbance (and particularly post-fire) recruitment by resprouters  
is lower than by non-resprouters (see e.g. Table S2). Some studies show no differences in initial  
450 recruitment (e.g. Knox and Clarke, 2006), although non-resprouters may show strategies that ensure  
more recruitment over a number of years (e.g. Zammit and Westoby, 1987). More systematic studies  
are required to characterise quantitatively the difference between resprouters and non-resprouters,  
but it would appear that reducing the recruitment of resprouters to ca. 10 % of that of non-resprouters  
is conservative. We therefore set the establishment rate of all resprouting PFTs to 10 % of that of the  
455 equivalent non-resprouting PFT.

#### 4 Model configuration and test

Each change in parameterisation was implemented and evaluated separately. For each change,  
the model was spun-up using detrended climate data from the period 1950-2000 and the standard  
lightning climatology (following the protocol outlined in Prentice et al., 2011)) until the carbon  
460 pools were in equilibrium. The length of the spin-up varies but is always more than 5000 yr. After  
spin-up, the model was run using a monthly lightning climatology from the Lightning Imaging  
Sensor–Optical Transient Detector High Resolution flash count ([http://gcmd.nasa.gov/records/GCMD\\_lohrmc.html](http://gcmd.nasa.gov/records/GCMD_lohrmc.html)), time-varying climate data derived from the CRU (Mitchell and Jones, 2005) and

National Centers for Environmental Prediction (NCEP) reanalysis wind (NOAA Climate Diagnostics  
Center, Boulder, Colorado, <http://www.cdc.noaa.gov/>) data sets as described in Prentice et al. (2011).  
We took the opportunity to correct an error in the NCEP wind inputs used by Kelley et al. (2013),  
but given that this correction was made for all of LPX-Mv1 runs this change has no impact on the  
differences caused by the new parameterisations.

We used the benchmarking system of Kelley et al. (2013) to evaluate the impacts of each change  
on the simulation of fire and vegetation processes. This benchmarking system quantifies differences  
between model outputs and observations using remotely-sensed and ground observations of a suite  
of vegetation and fire variables and specifically designed metrics to provide a “performance score”.  
We make the comparison only for the continent of Australia, since this is a highly fire-prone region  
(van der Werf et al., 2008; Giglio et al., 2010; Bradstock et al., 2012) and was the worst simulated in  
the original model (see Kelley et al., 2013). We used the benchmark observational datasets described  
in Kelley et al. (2013), with the exception of CO<sub>2</sub> concentrations, runoff, GPP and NPP. There are  
too few data points (< 10) from Australia in the runoff, GPP and NPP datasets to make comparisons  
statistically meaningful. We did not use the CO<sub>2</sub> concentrations because this requires global fluxes  
to be calculated.

We have expanded the Kelley et al. (2013) benchmarking system to include Australia-specific  
datasets for production and fire (Table 3). To benchmark production, we compared modelled 1 h  
fuel production to the Vegetation and Soil-carbon Transfer (VAST) fine litter production dataset for  
Australian grassland ecosystems (Barrett, 2001). Kelley et al. (2013) provide a burnt area benchmark  
based on the third version of the Global Fire Database (GFED3; Giglio et al., 2010). This has  
recently been updated (GFED4; Giglio et al., 2013). We re-gridded the data for the period (i.e. the  
period for which we have climate data to drive the LPX-Mv1 simulations) to 0.5° resolution to serve  
as a benchmark for the model simulations, although we continue to use GFED3 for comparison with  
results from Kelley et al. (2013). We also use a burnt area product for southeastern Australia based  
on ground observations of the extent of individual fires during the fire year (July through June) for  
the period July 1970 to June 2009 on a 0.001° grid (Bradstock et al., 2013). These data were  
re-gridded to 0.5° resolution for annual average and inter-annual comparisons with simulated burnt  
area for July 1996 to June 2005.

The difference between simulation and observation was assessed using the metrics described  
in Kelley et al. (2013). Annual average and inter-annual comparisons were conducted using the  
Normalised Mean Error metric (NME). Seasonal length was benchmarked by calculating the  
concentration of the variable in one part of the year for both model and observations, and comparing  
these concentrations with NME. Possible scores for NME run from 0 to  $\infty$ , with 0 being a perfect  
match. Changes in NME are directly proportional to the change in model agreement to observations,  
therefore a percentage improvement or degradation in model performance is obtained from the ratio  
of the original model to the new model score. NME takes a value of 1 when agreement is equal to

that expected when the mean value of all observations is used as the model. Following Kelley et al. (2013), we describe model scores greater/less than 1 as better/worse than the “mean null model” and we also use random resampling of the observations to develop a second “randomly resampled” null model. Models are described as better/worse than randomly resampled if they were less/more than two standard deviations from the mean randomized score. The values for the randomly resampling null model for each variable are listed in Table 4.

For comparisons using NME, removing the influence of first the mean, and then the mean and variance, of both simulated and observed values allowed us to assess the performance of the mapped range and spatial (for annual average and season length comparisons) or temporal (for inter-annual) patterns for each variable using NME.

We used the Mean Phase Difference (MPD) metric to compare the timing of the season and the Manhattan Metric (MM: Gavin et al., 2003; Cha, 2007) to compare vegetation type cover (Kelley et al., 2013). Both these metrics take the value 0 when the model agrees perfectly with the data. MPD has a maximum value of 1 when the modelled seasonal timing is completely out of phase with observations; whereas MM scores 2 when there is a perfect disagreement. Scores for the mean and random resampling null models for MM and MPD comparisons are given in Table 4.

The metric scores for each simulation were compared with the scores obtained with the original LPX (Table 5). Because many of the fire parameterisations in LPX were tuned to provide a reasonable simulation of fire, implementing individual improvements to these parameterisations can lead to a degradation of the simulation – we therefore use the performance scores for individual parameterisation changes only to help interpret the overall model performance. We only introduced resprouting after the other re-parameterisations had been made. The run that includes all the new parameterisations except resprouting is designated LPX-Mv1-nr and the run including resprouting is designated LPX-Mv1-rs.

#### **4.1 Testing the formulation of resprouting**

To assess the response of vegetation to the presence/absence of resprouting, we ran both LPX-Mv1-rs and LPX as described above for southeastern Australia woodland and forest ecosystems with  $\geq 20\%$  wood cover as determined by the International Satellite Land-Surface Climatology Project (ISLSCP) II vegetation continuous field (VCF) remotely-sensed dataset (Hall et al., 2006; DeFries and Hansen, 2009) (Fig. 8). Normal fire regimes were simulated until 1990, when a fire was forced burning 100 % of the grid cells, and killing (or causing to resprout, in the case of RS PFTs) 60 % of the plants. Fire was stopped for the rest of the simulation to assess recovery from this fire. As the proportion of individuals killed was fixed, this experiment only tested the RS scheme and not factors affecting mortality. The LPX simulation therefore serves as a test for NR PFTs in LPX-Mv1 as well. The simulated total foliage projected cover (FPC) in the years post-fire was compared against site-based remotely-sensed observations of inter-annual post-fire greening following fire in fire-prone sites with



Mediterranean or humid subtropical vegetation from several different regions of the world (Table S3), split into sites dominated by either RS and other fire adapted vegetation (normally Obligate Seeders – OS) as defined in Sect. 3.6 based on the dominant species listed in each study (Table S3).

540 (The use of observations from other regions of the world reflects the lack of observations of post-fire recovery in Australia.) We also used studies from boreal areas with low fire frequency to examine the response in ecosystems where fire-response traits are uncommon (Table S3). The comparison between simulated and observed regeneration was performed using a simple regeneration index (RI) that describes the % recovery of lost Normalized Difference Vegetation Index (NDVI) at a given  
545 time,  $t$ , after an observed fire:

$$RI_t = 100 \cdot \frac{QVI_t - \min QVI_{\text{postfire}}}{\overline{QVI_{\text{prefire}}}} \quad (35)$$

where  $QVI_t$  is the ratio of the vegetation index (VI) of the burnt areas at time  $t$  after a fire compared to that of either an unburnt control site or, in studies where a control site was not used, the average  
550 VI of the years immediately preceeding the fire;  $\min(QVI_{\text{postfire}})$  is the minimum QVI in the years immediately following the fire; and  $\overline{QVI_{\text{prefire}}}$  is the average QVI in the years immediately preceeding the fire. NDVI was the most commonly used remotely-sensed VI in the studies used for comparison. FPC has a linear relationship against NDVI (Purevdorj et al., 1998). However, this relationship differs between grass and woody plans (Xiao and Moody, 2005). As NDVI is normalised when  
555 used in Eq. (35), a direct conversion from FPC to NDVI is not necessary. Instead, we scaled for the different contributions from tree and grass, defining  $NDVI_{\text{sim}}$  based on the statistical model described in Sellers et al. (1996) and Lu and Shuttleworth (2002) (see Supplement, Eq. S1 to S4):

$$NDVI_{\text{sim}} = FPC_{\text{tree}} + 0.32 \cdot FPC_{\text{grass}} \quad (36)$$

560 where  $FPC_{\text{tree}}$  is the fractional cover of trees and  $FPC_{\text{grass}}$  of grasses.

A site or model simulation was considered to have recovered when vegetation cover reached 90 % of the pre-fire cover (i.e. when  $RI = 90$  %). Recovery times for each site are listed in Table S3. Note that RI is a measure of the recovery of vegetation cover, not recovery in productivity or biomass. If a site or model simulation simulation failed to recover before the end of the study, the recovery point  
565 was calculated by extending RI forward by fitting the post-fire data from the site to:

$$RI = 100 \cdot \left( 1 - \frac{1}{1 + p \cdot t} \right) \quad (37)$$

where  $p$  is the fitted parameter. The contribution of each site to the estimated mean and standard deviation of recovery time for a range of fire-adapted ecosystems was weighted based on the time  
570 since the last observation (Table S3). Sites that have observations during that time were given full weight, with weight decreasing exponentially with increasing time since the last observation.

## 5 Model performance

Evaluation of the model simulations focuses on changes in vegetation distribution (expressed through changes in the relative abundance of PFTs) and changes in burnt area (both total area burnt each year in each grid cell, i.e. fractional burnt area, and the seasonal distribution and timing of burning). We show the simulated change in tree cover (Fig. 8) and in mean annual burnt area (Fig. 9) for the original model compared to the simulations with LPX-M-v1 in both the resprouting (LPX-M-v1-rs) and non-resprouting (LPX-Mv1-nr) variants, as well as the differences between the two LPX-M-v1 simulations. We use benchmarking metrics to quantify the differences between the simulations (Table 5, Table S5). Following (Kelley et al., 2013), we calculate the metrics in three steps in order to take account of biases: Step 1 is a straight comparison; 2 is a comparison with the influence of the mean removed; 3 is with mean and variance removed.

As the NME and MM metric are the sum of the absolute spatial variation between the model and observations, the comparison of scores obtained by two different models shows the relative magnitude of their biases with respect to the observations, and the improvement can be expressed in percentage terms. Although we focus on vegetation distribution and fire, we have also evaluated model performance in terms of other vegetation characteristics, including fAPAR, net primary production, and height (Table S5), to ensure that changes in the model do not degrade the simulation of these characteristics.

### 5.1 LPX-Mv1-nr

The simulation of annual average burnt area for Australia in LPX-Mv1-nr is more realistic than in LPX: the NME score is 0.88–0.89 (better than the mean model) compared to scores for LPX of 1.00–1.01 (performance equal to or worse than the mean model). The change in NME (Table 5) is equivalent to a 13–14 % improvement in model performance. The improvement in annual burnt area can be attributed to an improved match to the observed spatial pattern of fire and a better description of spatial variance. The improved NME scores obtained after removing the influence of the mean and variance of both model outputs and observations (step 3 in Table 5) is due to the introduction of fire into climates without a pronounced dry season, such as southeastern Australia (Fig. 9) which results from the lightning re-parametrisation (Fig. S1). The improvement in spatial variability (step 2 in Table 5) is a result of decreased fire in the arid interior of the continent and an increase in fire in seasonally-dry areas of northern Australia (Fig. 9). The decrease in fire in fuel-limited regions of the interior is a result of a decrease in fuel load from faster fuel decomposition, resulting from the re-parameterisation of decomposition, and a decrease in grassland production resulting from the rooting depth re-parameterisation which leads to a decrease in the proportion of grass roots in the lower soil layer and increased water stress. Comparison of the simulated fine fuel production with VAST observations shows that the re-parameterisation of rooting depth improves simulation of fine

tissue production by 228 %. The improvement in the amount of fire in seasonally dry regions is a result of the re-parameterisation of fuel drying rates (Fig. S1).

LPX-Mv1-nr produces an improved simulation of the inter-annual variability (IAV) of fire by 15–42 % from at NME of 0.94–1.05 to 0.66–0.91 (Table 5) – now better than the mean null model score of 1.00 (Table 4). This improvement was due to the combination of the re-parameterisation of fuel drying time, which describes the impact of drier-than-normal conditions in certain years on fire incidence in northern and southeastern Australia, and a better description of litter decomposition in fine-fuel dominated grassland, which allows for a more realistic description of fuel limitation in dry years where last years fuel has decomposed and no new fuel is being produced.

Simulation of the length of the fire season is also improved by 6–8 %. The improved NME score of 1.31–1.32 is better than the randomly-resampled null model ( $1.32-1.36 \pm 0.02 -0.0073$ ), but not the mean model 1.00 (Table 4). Improvements come from the parameterisation of lightning, drying times and fuel decomposition. The new lightning parameterisation leads to an increase in the length of the fire season, because fire starts occur over a longer period in coastal regions. The changes in drying time produce an earlier start to the fire season in all regions of Australia. The change to the decomposition parameterisation leads to decreased fire in the arid interior of Australia towards the end of the dry season by reducing fuel loads.

Despite an improvement of 68–76 %, LPX-Mv1-nr still performs poorly for southeastern Australia when compared against ground observations. The score is better when satellite observations are used for comparison but NME scores are still worse than the randomly resampled null model (Tables S4 and S5). The model simulates too much fire in the Southern Tablelands (Fig. 9) but simulation of fire in more heavily-wooded regions is more accurate, with burnt areas of around ca. 1–5 % in agreement with observations.

The improvement in vegetation distribution is largely due to simulating more realistic transitions between forest and grassland, chiefly through the parameterisation of adaptive bark thickness (which by itself yields a 37 % improvement in performance) but also through improved competition between trees and grasses for water, which results from the re-parameterisation of rooting depth. The degradation of the MM score for tree cover only (0.17 for LPX-Mv1-nr compared to 0.16 for LPX) is because the new model simulates slightly too much tree cover in southeastern Australia. The boundaries between closed forests and savanna in this region are still too sharp (Fig. 8).

Performance is degraded in LPX-Mv1-nr relative to LPX for annual average and inter-annual fAPAR (from 1.11 and 1.01 to 1.31 and 1.83 respectively) and cover of evergreen/deciduous types (0.29 to 0.72). fAPAR was already on average 59 % higher in LPX compared to observations (Table 5), mostly due to simulating too much tree cover in southeastern Australia (Fig. 8b). The introduction of adaptive bark thickness has caused an even higher average fAPAR value (Table 5) from the spread of woody vegetation into fire-prone areas (Fig. 8c). However, the inclusion of adaptive bark thickness helped improve the spatial pattern and variability (Table 5) from 0.71 to

0.57 by increasing tree cover in the north and by allowing a smoother transition between dense,  
645 high fAPAR forest near the coast and lower fAPAR grassland and desert in the interior. An MM  
comparison for phenology in areas where both LPX and LPX-Mv1-nr have woody cover shows  
little change in simulated phenology, with both scoring 0.29.

## 5.2 LPX-Mv1-rs

Including resprouting in LPX-Mv1 (LPX-Mv1-rs) produces a more accurate representation of the  
650 transition from forest through woodland/savanna to grassland (Fig. 8) and improves the simulations  
of vegetation cover by 2 % compared to LPX-Mv1-nr and tree cover by 6 %. There is also a significant  
improvement in phenology compared to LPX-Mv1-nr, with NME scores changing from 0.72 in  
LPX-Mv1-nr to 0.46 in LPX-Mv1-rs (Table 5). The simulation of burnt area also improves: the  
NME for LPX-Mv1-rs is 0.85–0.88 compared to 0.88–0.89 for LPX-Mv1-nr, representing an overall  
655 improvement of 1–4%. This improvement is equally due to the decrease in burnt area resulting from  
increased tree cover in southwestern Queensland (QL) and southeastern Australia (Fig. 10).

The simulated distribution of trees in climate space is improved in LPX-Mv1-rs compared to LPX.  
Trees are slightly more abundant at values of  $\alpha$  (the ratio of actual to equilibrium evapotranspiration)  
between 0.2 and 0.4 in LPX-Mv1-rs than in LPX; while in humid climates, where  $\alpha > 0.8$ , trees  
660 are less abundant than in LPX. The simulated abundance of trees in LPX-Mv1-rs is in reasonable  
agreement with observations (Fig. 6)

The simulated distribution of RS dominance over NR PFTs is plausible. The observations indicate  
that aerial (apical and epicormic) resprouters are most abundant at intermediate moisture levels ( $\alpha$   
between 0.4 and 0.6) but occur at higher moisture levels; the simulated abundance of RS is maximal  
665 at  $\alpha$  values between 0.4–0.5, and although it declines more rapidly at higher moisture levels than  
shown by the observations nevertheless resprouting still occurs in moist environments. RS have  
a competitive advantage over NR when  $\alpha$  is between 0.5 and 0.8 (Fig. S2).

The simulated regeneration after fire in RS-dominated communities in southeastern Australia is  
fast: NDVI<sub>sim</sub> reaches 90 % of pre-fire values within 7 yr, whereas post-fire regrowth takes 30 yr  
670 in the simulations that do not include RS (Fig. 7). Observations show that post-fire recovery in  
RS-dominated vegetation takes between 4–14 yr with a mean recovery time of 7 yr, whereas the  
recovery takes 8–16 yr (with a mean of 13 yr) in OS-dominated communities; and 7–22 yr (mean of  
19) in boreal ecosystems.

## 6 Discussion

675 The introduction of new parameterisations in the LPX DGVM improves the simulation of vegetation  
composition and fire regimes across the fire-prone continent of Australia. The overall improvement  
in performance in LPX-Mv1-rs compared to LPX is 15–18 % for burnt area; 17–38 % for inter-annual

variability of fire; and 33 % for vegetation composition. These improvements result from the combination of all the new parameterisations. The introduction of individual parameterisations frequently led to a degradation of performance because LPX, in common with many other fire-enabled DGVMs, was tuned to produce a reasonably realistic simulation of burnt area. Our approach here has been to develop realistic parameterisations based on analysis of large data sets; the model was not tuned against fire observations. Post-fire aerial resprouting behaviour has not been included in DGVMs until now, although resprouting has been included in forest succession models (e.g. Loehle, 2000) and the BORFIRE stand-level fire response model (Groot et al., 2003). Adaptive bark thickness has not been included in any vegetation model before, despite considerable within- and between-ecosystem variation in this trait, and the fact that the average thickness within an ecosystem shifts with changes in fire regime. The incorporation of both processes is responsible for a significant part of the overall model improvement in LPX-Mv1-rs vs. LPX, and produces more realistic vegetation transitions from forests to woodland/savanna and, as shown by the regrowth comparisons, a more dynamically-responsive DGVM.

The rapid post-fire regeneration in RS dominated ecosystems is well reproduced using the modelling framework adopted here. However, simulated NR ecosystem recovery is slower than observations (Fig. 7). This might, at least in part, be because the model does not yet include fire-recovery strategies found in other ecosystems. There are other post-fire recovery mechanisms including resprouting from basal or underground parts of trees and obligate seeding (Clarke et al., 2013). We have focused on aerial resprouting because this has the fastest impact on ecosystem recovery (Crisp et al., 2011; Clarke et al., 2013) and thus the greatest potential to influence carbon stocks and vegetation patterns. However, basal/collar resprouting is important in shrubs (Harrison et al., 2014), and thus should be included in models that simulate shrub PFTs explicitly. The “obligate seeder” strategy (i.e. the release of seeds from canopy stores by fire or the triggering of germination of seeds stored in the soil by smoke or fire-produced chemicals) also leads to a more rapid recovery than non-stimulated regeneration from seed. Obligate seeders are found in a wider range of ecosystems than resprouters, including boreal ecosystems.

The ability to include a wider range of post-fire responses is currently limited by the availability of large data sets which could be used to develop appropriate parameterisations. Synthesis of the quantitative information available from the vast number of field studies on these traits would be useful for the modelling community. A similar argument could be made for information on rooting depth: although this is a trait that varies considerably within PFTs and depending on environmental conditions (Schenk and Jackson, 2002b, 2005), lack of species-level data has prevented us from implementing an adaptive deep root fraction within LPX-Mv1.

Despite the improvement in the simulation of fire in southeastern Australia, LPX-Mv1-rs simulates ca 5 times more fire than observed in some parts of QLD, NSW and VIC, where, although the

natural vegetation is woodland/savanna, the proportion of the land used for agriculture (crops, pasture) is high  $> 80\%$  (Klein Goldewijk et al., 2011). The overall impact of agriculture is to reduce burnt area dramatically (Archibald et al., 2009; Bowman et al., 2009), through increasing landscape fragmentation (Archibald et al., 2012) and preventing fires from spreading. Incorporating land fragmentation into LPX-Mv1 could provide a more realistic simulation of fire in agricultural areas, such as southeastern Australia.

We have used the benchmarking system described in Kelley et al. (2013) to assess the performance of the two new versions of LPX-Mv1 and to determine which new parameterisations contributed to improvements in performance. However, we needed to modify the existing system to take into account of the recent update of the global burnt area product (GFED4) and to improve comparisons for Australia by using alternative burnt area products and the VAST dataset for the assessment of fine fuel production. As pointed out by Kelley et al. (2013), the incorporation of new processes into DGVMs will require the creation of new benchmarks. We have used the conceptual model of Clarke et al. (2013), which is based on extensive field observations, to evaluate our simulations of RS-dominance in a qualitative way. Spatially-explicit data on the distribution and abundance of resprouting species is required to test our simulations quantitatively. An Australian dataset of RS abundance in fire-prone ecosystems is currently under development (Harrison et al., 2014); it would be useful if such a dataset were available for a wider range of ecosystems and climates. Similarly, we have shown that an adaptive bark thickness parameterisation produces qualitatively plausible changes in average bark thickness in different regions and under different fire regimes, using field-based studies. A spatially-explicit database of bark thickness would enable us to test the simulated patterns in bark thickness across ecosystems and fire regimes in a quantitative way.

## 7 Conclusions

Fire-vegetation interactions involve many processes and feedbacks. It is possible to tune a model to provide the best fit to an emergent property of the fire-vegetation system, such as observed burnt area, in multiple ways. Good simulations of burnt area can be obtained through many different combinations of parameter values. Such tuning can also lead to the assignment of parameter values that are wrong. Our approach in developing new fire parameterisations for LPX-Mv1 has been to rely on the analysis of data directly relevant to each individual process. This approach is possible because of the steadily-increasing amount of data available through satellite observations and geographically-explicit syntheses of ground observations. The new model incorporates a more realistic generic description of fire processes, and has been shown to produce a better simulation of vegetation properties and fire regimes across Australia. Further tests are required to establish that it produces the expected improvement in the simulation of fire-prone vegetation worldwide.

**Supplementary material related to this article is available online at:**

750 <http://www.geosci-model-dev.net/0/1/2014/gmd-0-1-2014-supplement.pdf>.

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Benchmarking datasets and scripts for data-model comparison metrics from both Kelley et al. (2013) and the updates described here are available at <http://bio.mq.edu.au/bcd/benchmarks/>. Information and code used for data analysis are available at [https://bitbucket.org/teambcd/lpx2013\\_data\\_analysis](https://bitbucket.org/teambcd/lpx2013_data_analysis). Benchmarking and data analysis were scripted using R (R Development Core Team) and the quantreg (Koenker, 2013), raster (van Etten and Hijmans, 2013), glm (R Core Team, 2013), RNetCDF (Michna, 2012) and Hmisc (Harrell Jr., 2012) packages.

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**Table 1.** Plant functional type (PFT)-specific values used in LPX-Mv1. TBE denotes tropical broadleaf evergreen tree, TBD denotes tropical broadleaf deciduous tree, tBE denotes temperate broadleaf evergreen tree, and tBD temperate broadleaf deciduous tree. Values for resprouting variants (RS) of each of these PFTs are given in brackets. If no resprouting value is given then the resprouting PFT takes the normal PFT value. tNE denotes temperate needleleaf evergreen; BNE denotes boreal needleleaf evergreen; BBD denotes boreal broadleaf deciduous; C<sub>3</sub>: C<sub>3</sub> grass; C<sub>4</sub> grass. BT par<sub>*i*</sub> is the bark thickness parameter used in Eqs. (25) and (26);  $k_{10,leaf}$  and  $k_{10,wood}$  are the reference litter decomposition rates of leaf and grass used in Eq. (2);  $Q_{10}$  is the parameter describing woody litter decomposition rate changes with temperature in Eq. (21).

	TBE	TBD	tNE	tBE	tBD	BNE	BBD	C <sub>3</sub>	C <sub>4</sub>	Source
fraction of roots in upper soil layer	0.80	0.70	0.85	0.80	0.80	0.85	0.80	0.90	0.85	Section 3.4; Table 2; Fig. 3
BT par <sub>lower</sub>	0.00395 (0.0292)	0.00463 (0.0109)	0.00609	0.0125 (0.0286)	0.00617 (0.0106)	0.0158	0.00875	N/A	N/A	Section 3.5;
BT par <sub>mid0</sub>	0.0167 (0.0629)	0.0194 (0.0568)	0.0257	0.0302 (0.0586)	0.0230 (0.0343)	0.0261	0.0316	N/A	N/A	Table S1; Fig. 4
BT par <sub>upper</sub>	0.0399 (0.183)	0.0571 (0.188)	0.0576	0.0909 (0.156)	0.0559 (0.106)	0.0529	0.112	N/A	N/A	
$k_{10,leaf}$	0.93	1.17	0.70	0.86	0.95	0.78	0.94	1.20	0.97	Section 3.3;
$k_{10,wood}$	0.039	0.039	0.041	0.104	0.104	0.041	0.104	N/A	N/A	Brovkin et al. (2012)
$Q_{10}$	2.75	2.75	1.97	1.37	1.37	1.97	1.37	N/A	N/A	

**Table 2.** Translation between LPX Plant Functional Types (PFTs) and the vegetation trait information available for sites which were used to provide rooting depths.

LPX PFT	Rooting depth		Site information		
	vegetation type from Fig. 3	Site leaf type	Site Phenology	Site Climate	Site Life form
TBE tBE	Evergreen Broadleaf	Broad only	Evergreen	Any	Tree only
TBD	Drought Deciduous Broadleaf	Broad only	Drought deciduous	Any	Tree only
tBD BBD	Cold Deciduous Broadleaf	Broad only	Cold/Winter deciduous	Any	Tree only
tNE BNE	Needle-leaf	Needle only	Any	Any	Tree only Tree only
C <sub>3</sub> Grass	Cold grassland	Any	Any	MTCO ≤ 15.5 °C	Grass or Herb
C <sub>4</sub> Grass	Warm grassland	Any	Any	MTCO > 15.5 °C	Grass or Herb

**Table 3.** Summary description of the benchmark datasets.

Dataset	Variable	Type	Period	Comparison	Reference
GFED4	Fractional burnt area	Gridded	1996–2005	Annual average, seasonal phase and concentration, inter-annual variability	Giglio et al. (2013)
GFED3	Fractional burnt area	Gridded	1996–2005	Annual average, seasonal phase and concentration, inter-annual variability	Giglio et al. (2010)
SE ground observations	Fractional burnt area	Gridded	1996–2005	Annual average	Bradstock et al. (2013)
VAST	Above ground fine litter production	Site	1996–2005	Annual average, inter-annual variability	Barrett (2001)
ISLSCP II vegetation continuous fields	Vegetation fractional cover	Gridded	Snapshot 1992/1993	Fractional cover of bare ground, herbaceous and tree; tree cover split into evergreen or deciduous, and broadleaf or needleleaf	DeFries and Hansen (2009)
SeaWiFS	Fraction of absorbed photosynthetically active radiation (fAPAR)	Gridded	1998–2005	Annual average, seasonal phase and concentration, inter-annual variability	Gobron et al. (2006)
Canopy height	Annual average height	Gridded	2005	Direct comparison	Simard et al. (2011)

**Table 4.** Scores obtained using the mean of the data (Data mean), and the mean and standard deviation of the scores obtained from random-resampled null model experiments (Bootstrap mean, Bootstrap SD). Step 1 is a straight comparison; 2 is a comparison with the influence of the mean removed; 3 is with mean and variance removed. The scores given for fire represent the range of scores over all fire datasets for that comparison. Scores for individual datasets can be found in Table S4.

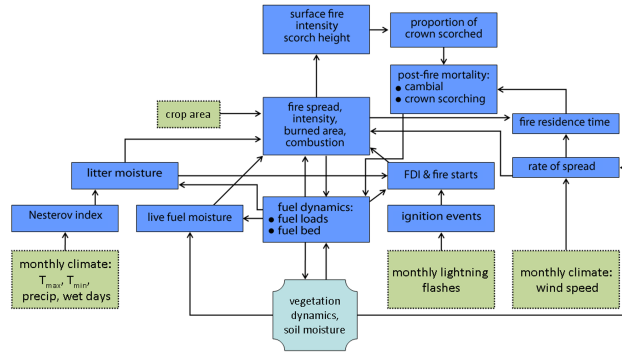
Variable	Step	Measure	Time period	Mean	Bootstrap mean	Bootstrap SD
Fire: All Aus	1	Annual average	1997–2006	1.00	1.14–1.25	0.0028–0.015
	2			1.00	1.24–1.26	0.0037–0.015
	3			1.00	1.28–1.30	0.0053–0.016
	2	IAV		1.00	1.31–1.50	0.34–0.36
	1	Seasonal Concentration		1.00	1.32–1.36	0.0073–0.020
	N/A	Phase		0.39–0.45	0.44–0.47	0.0015–0.0046
Fire: SE Aus	1	Annual average		1.00	1.18–1.19	0.024–0.026
	2			1.00	1.10–1.19	0.024–0.027
	3			1.00	1.20–1.21	0.024–0.025
	2	IAV		1.00	1.24–1.32	0.33–0.37
	1	Seasonal Concentration		1.00	1.31–1.33	0.043–0.053
	N/A	Phase		0.44–0.47	0.47	0.010–0.011
Veg cover	N/A	life forms	1992–1993	0.71	0.89	0.0018
	N/A	tree cover		0.43	0.54	0.0015
	N/A	herb cover		0.49	0.66	0.0017
	N/A	bare ground		0.46	0.56	0.0017
	N/A	broadleaf		0.83	0.96	0.0041
	N/A	evergreen		0.70	0.87	0.0032
fine litter NPP	1	Annual average	1997–2005	1.00	1.44	0.21
	2			1.00	1.44	0.22
	3			1.00	1.43	0.095
fAPAR	1	Annual average	1997–2005	1.00	1.33	0.015
	2			1.00	1.33	0.015
	3			1.00	1.32	0.014
	2	IAV		1.00	1.23	0.32
	3			1.00	1.35	0.36
	1	Seasonal Conc		1.00	1.46	0.014
	2			1.00	1.46	0.014
	3			1.00	1.45	0.014
	N/A	Phase		0.30	0.38	0.0033
Height	1	Annual average	2005	1.00	1.32	0.016
	2			1.00	1.32	0.016
	3			1.00	1.31	0.016

**Table 5.** Scores obtained for the individual parameterisation experiments, and for the LPX-Mv1-nr and LPX-Mv1-rs experiments compared to the scores obtained for the LPX experiment. The metrics used are the normalised mean error (NME), the mean phase difference (MPD) and the Manhattan Metric (MM). S1 are step 1 comparisons, S2 are step 2; and S3 are step 3. The individual parameterisation experiments are: Lightn: lightning re-parameterisation, Drying: fuel drying-time re-parameterisation, Roots: rooting depth re-parameterisation, Litter: litter decomposition re-parameterisation; Bark: inclusion of adaptive bark thickness. LPX-M-v1-nr incorporates all of these parameterisations and LPX-M-v1-rs incorporates resprouting into LPX-Mv1-nr. Numbers in bold are better than the original LPX model; numbers in italics are better than the mean null model; \* means better than the random-resampled null model. The scores given for fire represent the range of scores over all fire datasets for that comparison. Scores for comparisons against individual datasets can be found in Table S5.

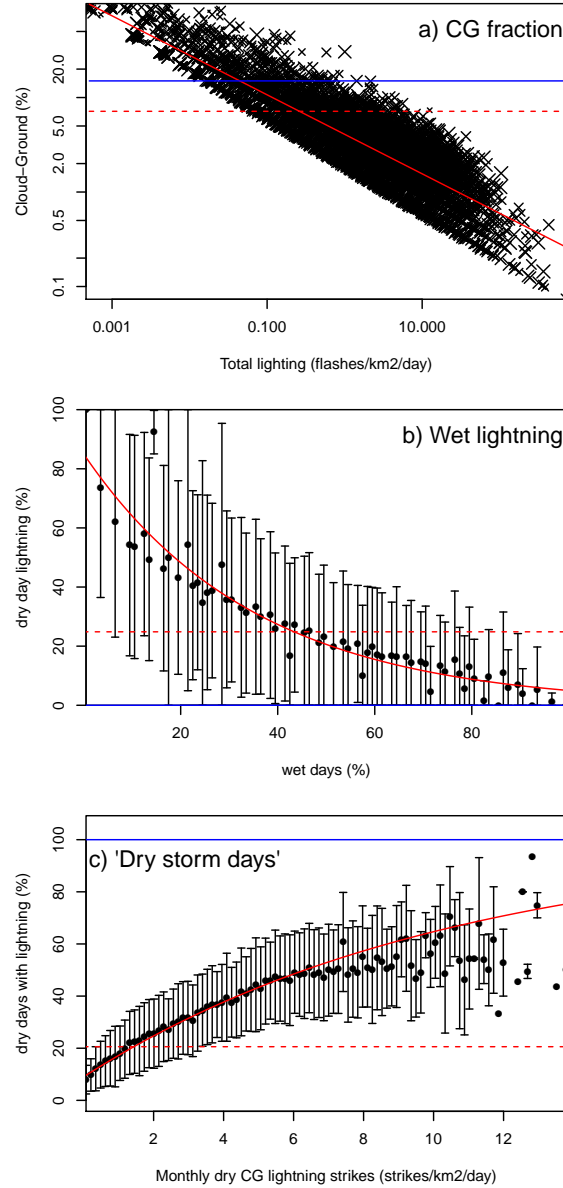
Variable	Metric	Measure	LPX	Lightn	Drying	Roots	Litter	Bark	LPX-M v1-nr	LPX-M v1-rs
Burnt area	Mean	Annual Average	0.082	0.12	0.084	0.086	0.02	0.003	0.049	0.050
	Mean ratio		1.13–1.21	1.64–1.77	1.15–1.24	1.18–1.27	0.28–0.29	0.039–0.043	0.67–0.72	0.69–0.74
	NME S1	Annual Average	1.00*–1.01*	1.24*–1.29	1.00*–1.02*	1.00*–1.02*	<b>0.90*–0.93*</b>	<b>0.88*–0.90*</b>	<b>0.88*–0.89*</b>	<b>0.85*–0.88*</b>
	NME S2		<i>0.97*–0.97*</i>	1.06*–1.09*	<i>0.97*–0.98*</i>	<b>0.97*–0.97*</b>	1.03*–1.04*	1.02*–1.02*	<b>0.90*–0.94*</b>	<b>0.89*–0.93*</b>
	NME S3		1.20*–1.22*	1.32–1.32	1.21*–1.23*	1.20*–1.23*	1.22–1.23*	1.38–1.39	<b>1.10*–1.12*</b>	<b>1.09*–1.09*</b>
	NME S2	Inter-annual variability	<i>0.94*–1.05*</i>	1.05*–1.06	<i>0.97*–1.08*</i>	<i>0.97*–1.17*</i>	<b>0.89–1.03*</b>	1.00*–1.03*	<b>0.66*–0.91</b>	<b>0.68*–0.90*</b>
	NME S1	Seasonal Conc.	1.39–1.43	<b>1.30*–1.33</b>	1.35*–1.43	1.36*–1.44	<b>1.31*–1.44</b>	<b>1.31*–1.44*</b>	<b>1.31*–1.32*</b>	<b>1.31*–1.32*</b>
	MPD	Phase	<i>0.44*–0.50</i>	<b>0.38*–0.46*</b>	<i>0.44*–0.50</i>	<i>0.44*–0.49*</i>	0.57–0.57	0.53–0.59	<i>0.49*–0.52</i>	<i>0.49*–0.52</i>

**Table 5.** Continued.

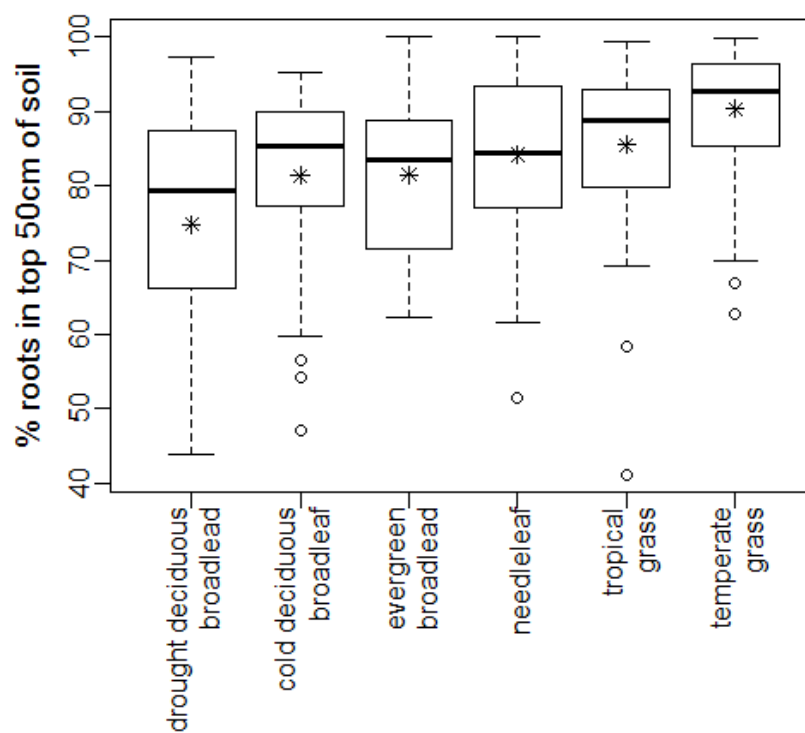
Variable	Metric	Measure	LPX	Lightn	Drying	Roots	Litter	Bark	LPX-M v1-nr	LPX-M v1-rs
burnt area: SE Aus	Mean	Annual Average	0.048	0.099	0.053	0.051	0.012	0.002	0.024	0.024
	Mean ratio		6.00–10.9	12.4–22.6	6.68–12.2	6.37–11.6	1.55–2.83	0.25–0.49	3.07–6.61	3.12–5.68
	NME S1	Annual Average	4.03–7.19	7.97–14	4.35–7.67	4.23–7.59	<b>1.59–2.40</b>	0.81*–0.92*	<b>2.29–4.27</b>	<b>2.33–3.67</b>
	NME S2		3.58–6.13	5.07–7.91	3.6– <b>6.06</b>	3.61–6.21	<b>1.78–2.99</b>	<b>1.05*–1.08*</b>	<b>2.50–4.75</b>	<b>2.53–4.20</b>
	NME S3		1.41–2.07	<b>1.23–1.35</b>	<b>1.35–1.37</b>	<b>1.38–1.40</b>	<b>1.22–1.25</b>	<b>1.18*–1.22</b>	<b>1.29–1.29</b>	<b>1.28–1.30</b>
	NME S2	Inter-annual variability	8.59–16.6	10.1–19.3	9.05–17.5	10.1–19.4	<b>3.83–7.65</b>	<b>1.27–2.33</b>	<b>5.56–11.5</b>	5.71–11.2
Veg cover	Mean	Trees	0.034	0.011	0.022	0.034	0.059	0.075	0.042	0.049
	Mean ratio		0.4	0.13	0.26	0.4	0.69	0.88	0.49	0.58
	Mean	Herb	0.44	0.34	0.45	0.44	0.55	0.57	0.55	0.55
	Mean ratio		0.65	0.5	0.65	0.65	0.81	0.84	0.80	0.81
	Mean	Bare ground	0.52	0.65	0.53	0.52	0.39	0.35	0.41	0.4
	Mean ratio		2.79	3.45	2.83	2.77	2.08	1.88	2.18	2.12
	Mean	Phenology	0.066	0.014	0.042	0.063	0.12	0.15	0.10	0.12
	Mean ratio		0.13	0.026	0.081	0.12	0.23	0.28	0.20	0.22
	Mean	Leaf type	0.055	0.01	0.035	0.056	0.1	0.14	0.096	0.11
	Mean ratio		0.094	0.018	0.059	0.096	0.18	0.24	0.17	0.18
Veg Cover	MM	Life Form	0.77*	0.96	0.79*	<b>0.76 *</b>	<b>0.59 *</b>	<b>0.56 *</b>	<b>0.59 *</b>	<b>0.58*</b>
		Trees	0.16*	0.17*	0.17*	0.17*	0.17*	0.19*	0.17*	0.16*
		Herb	0.66	0.77	0.67	<b>0.65*</b>	<b>0.53*</b>	<b>0.52*</b>	<b>0.51*</b>	<b>0.51*</b>
		Bare ground	0.72	0.95	0.73	<b>0.71</b>	<b>0.49 *</b>	<b>0.42 *</b>	<b>0.51 *</b>	<b>0.49*</b>
		Phenology	0.29*	0.33*	<b>0.24*</b>	0.29*	0.61*	0.81*	0.72	0.46
		Leaf type	0.51*	1.01	0.62*	<b>0.46*</b>	<b>0.34*</b>	<b>0.27*</b>	<b>0.15*</b>	<b>0.19*</b>
Fine NPP	Mean	Annual Average	628	112	192	180	177	176	181	202
	Mean ratio		2.67	0.5	0.85	0.8	0.78	0.80	0.82	0.90
	NME S1		2.62	<b>0.96*</b>	<b>0.79*</b>	<b>0.78*</b>	<b>0.82*</b>	<b>1.13*</b>	<b>0.80*</b>	<b>0.73*</b>
	NME S2		1.47	<b>0.83*</b>	<b>0.79*</b>	<b>0.78*</b>	<b>0.83*</b>	<b>1.22*</b>	<b>0.79*</b>	<b>0.74*</b>
	NME S3		0.97*	<b>0.91*</b>	1.01*	<b>0.89*</b>	1.01*	2.00	0.99*	<b>0.87*</b>
fAPAR	Mean	Annual Average	0.19	0.12	0.19	0.18	0.24	0.26	0.22	0.22
	Mean ratio		1.59	1.02	1.56	1.55	2.02	2.18	1.83	1.87
	NME S1	Annual Average	1.11*	<b>0.98 *</b>	1.11*	<b>1.07 *</b>	1.61	1.8	1.31	1.35
	NME S2		0.69 *	0.97 *	0.72 *	<b>0.68 *</b>	0.7 *	<b>0.69 *</b>	<b>0.61 *</b>	<b>0.61 *</b>
	NME S3		0.71 *	1.21*	0.76 *	0.71 *	<b>0.57 *</b>	<b>0.51 *</b>	<b>0.57 *</b>	<b>0.54 *</b>
	NME S2	Inter-annual variability	1.01	1.11	1.01	<b>0.97</b>	2.44	2.86	1.83	1.85
	NME S3	Seasonal Conc.	1.34*	1.44	1.35*	1.36*	<b>1.31*</b>	<b>1.31*</b>	<b>1.32*</b>	<b>1.33 *</b>
	MPD	Phase	0.25 *	0.25 *	0.25 *	<b>0.24 *</b>	0.25 *	0.25 *	<b>0.24 *</b>	<b>0.24*</b>
height	Mean	Annual Average	0.5	0.2	0.29	0.5	0.84	1.03	0.39	0.63
	Mean ratio		0.056	0.022	0.033	0.057	0.096	0.12	0.045	0.072
	NME S1		1.07*	1.1*	1.09*	1.07*	<b>1.02*</b>	<b>1.01*</b>	1.08*	<b>1.05*</b>
	NME S2		0.94*	0.98*	0.97*	0.94*	<b>0.91*</b>	<b>0.9*</b>	<b>0.96*</b>	<b>0.94*</b>
	NME S3		1.25*	1.39	1.31*	1.26*	<b>1.11 *</b>	<b>1.08*</b>	<b>1.18 *</b>	<b>1.13*</b>



**Fig. 1.** Description of the structure of the fire component of LPX, reproduced from Prentice et al. (2011). Inputs to the model are identified by green boxes, outputs from the vegetation dynamics component of the model are identified by light blue boxes, and internal processes and exchanges that are explicitly simulated by the fire component of the model are identified by blue boxes.

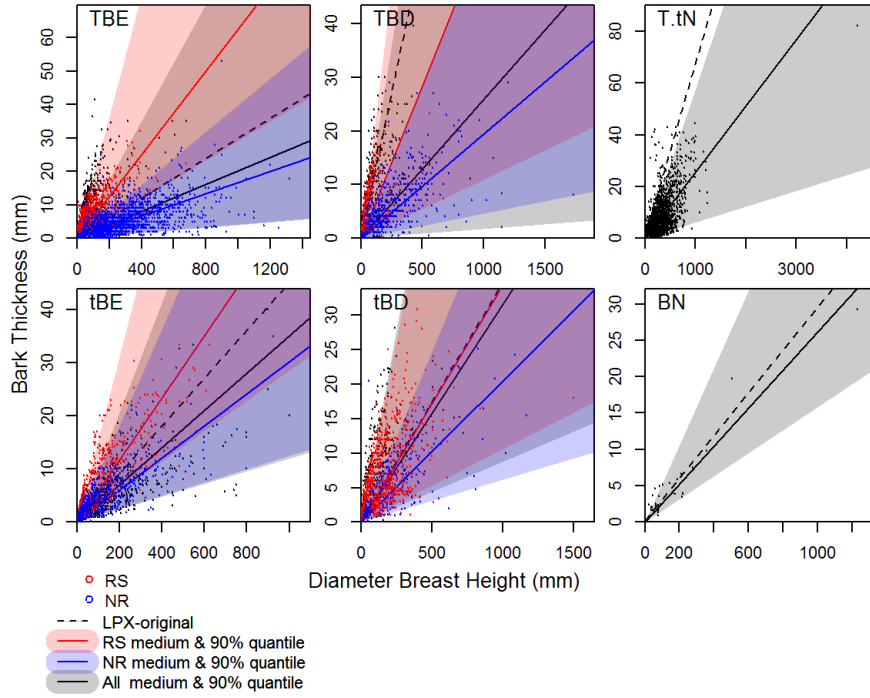


**Fig. 2.** Observed relationships between **(a)** total and cloud-to-ground lightning flashes, **(b)** the percentage of dry lightning with respect to the number of wet days per month, and **(c)** percentage of dry days with lightning with respect to monthly dry lightning strikes. These analyses are based on the Lightning Image Sensor (LIS) remote sensed data set (Christian et al., 1999; Christian, 1999) and NLDN ground observation of lightning strikes (Cummins and Murphy, 2009) for North America. The red line shows best-fit used by LPX-Mv1, the red dotted line shows the mean of the observations, and the blue line shows the relationship used in LPX. To aid visualisation, observations were binned every 1 % **(b)** or 0.1 strikes **(c)** along the x-axis, with the dots showing the mean of each bin and the error bars showing the standard deviations.

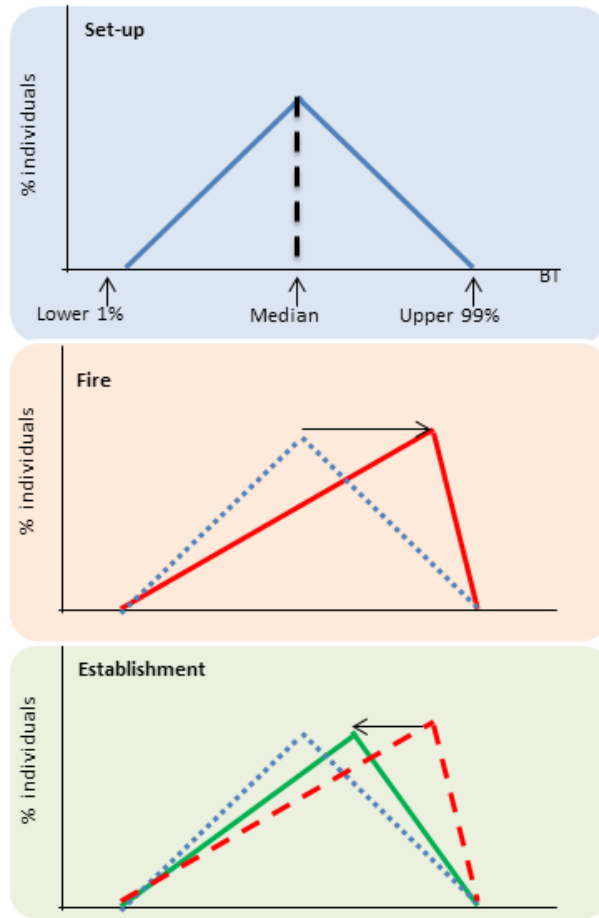


**Fig. 3.** Proportion of roots in the upper 50 cm of the soil by Plant Functional Type (PFT). The data were derived from Schenk and Jackson (2002a, 2005) and reclassified into the PFT recognized by LPX as shown in Table 2.

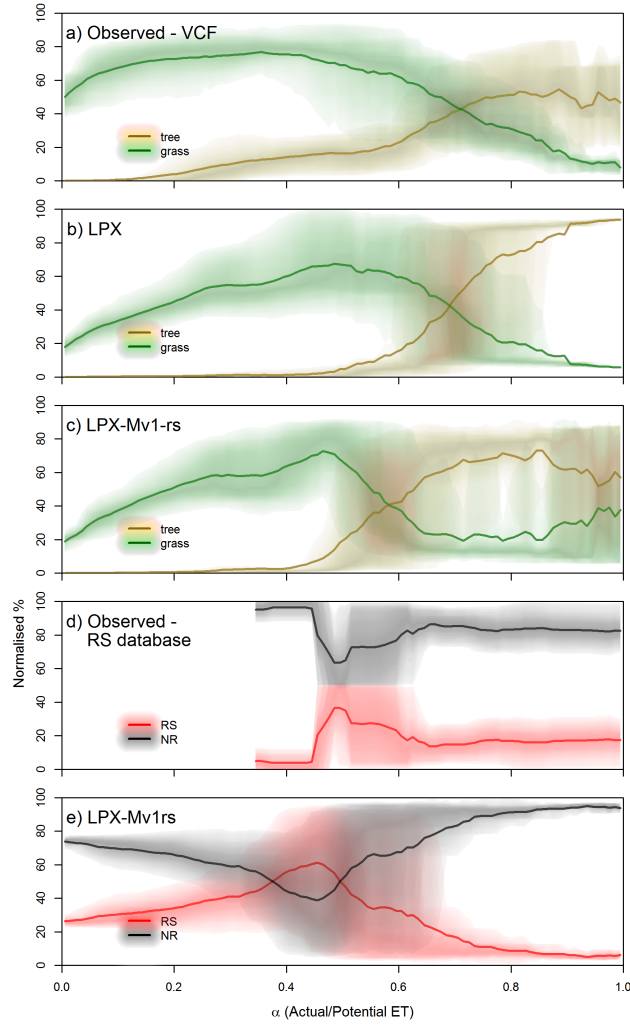




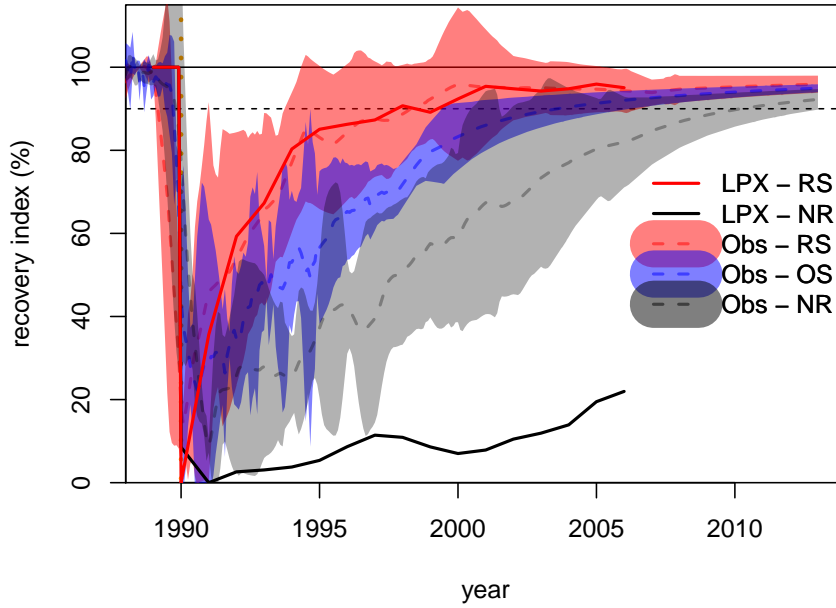
**Fig. 4.** Bark thickness (BT) vs. diameter at breast height for each LPX Plant Functional Type (PFT). Red dots show data used to constrain BT parameters in Table 1 for resprouting (RS) PFTs in LPX-Mv1-rs; blue dots show data from non-resprouting (NR) PFTs in LPX-Mv1-rs. Red, blue and grey dots are used to distinguish the PFTs in LPX-Mv1-nr. Red and blue lines show best fit lines. Red/blue shaded areas show 90 % quantile ranges. Black line/shaded area shows the best fit and 90 % range for all points. The black dotted line is the relationship used in LPX-M.



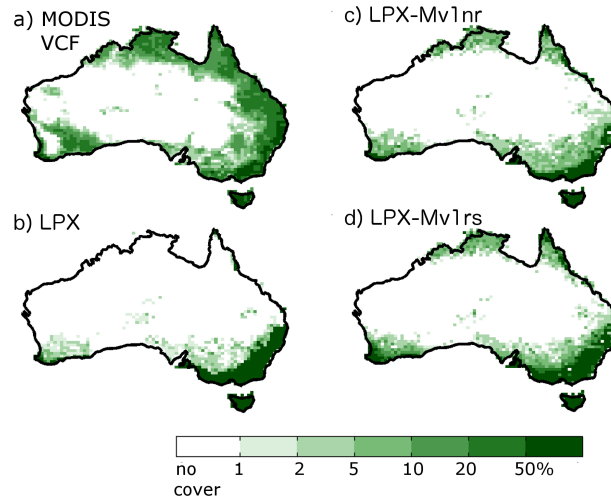
**Fig. 5.** Illustration of the variable bark thickness scheme. The initial set-up is based on parameter values (Table 1) obtained from Fig. 4. Fire preferentially kills individual plants with thin bark, changing the distribution towards individuals with thicker bark. Establishment shifts the distribution back towards the initial set-up.



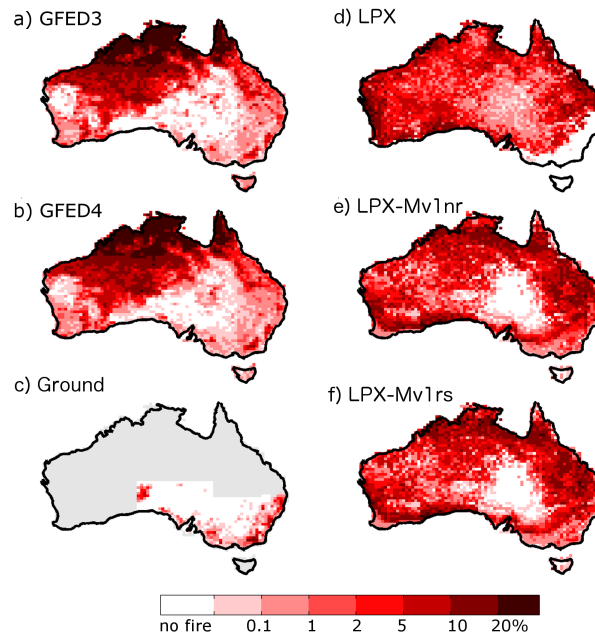
**Fig. 6.** Comparison of the simulated abundance of grass, tree and resprouting trees along the climatic gradient in moisture, as measured by  $\alpha$  (actual: potential evapotranspiration). Remotely sensed observations (a) of tree and grass cover from (DeFries and Hansen, 2009) compared to distribution of grass and trees simulated (b) by LPX and (c) LPX-Mv1-rs. (d) Observations of the abundance of aerial resprouters (RS – red) and other species (NR – black) from Harrison et al. (2014) compared to (e) RS (red) and non-resprouting (NR) PFTs (black) simulated by LPX-Mv1-rs. Note that some of the species included in the observed NR category may exhibit post-fire recovery behaviours such as underground (clonal) regrowth.  $\alpha$  was calculated as described by Gallego-Sala et al. (2010) in (a) and (d); and simulated by the relevant model in (b), (c) and (e). Abundance in (d) and (e) is normalised to show the % of the total vegetative cover of each category. Solid lines denote the 0.1 running mean and shading denotes the density of sites based on quantiles for each 0.1 running interval of  $\alpha$ .



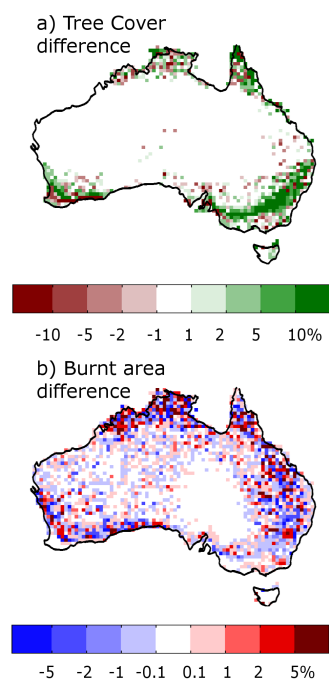
**Fig. 7.** Comparison of the time taken for leaf area (as indexed by total foliage projective cover, FPC), to recover after fire in different ecosystems, as shown in the LPX-Mv1-rs simulations and from observations. For comparison with the observations, which were all made after a significant loss of above-ground biomass through fire, the LPX simulations show recovery after a loss of 60% of the leaf area. Red denotes ecosystems dominated by above-ground resprouting (RS) species; blue denotes ecosystems dominated by other fire-adapted species, mostly obligate seeders (OS); black denotes vegetation which does not display specific fire adaptations (NR). The solid lines show LPX simulations; dotted lines show the mean of the relevant observations; the shaded areas show interquartile ranges of the relevant observations. The plots show that LPX-M-v1 reproduces the observed recovery rate in ecosystems dominated by resprouting species; recovery in ecosystems lacking resprouting trees is slower than observed, which could either reflect issues with simulated growth rates or the absence of other forms of fire adaptation.



**Fig. 8.** Comparison of % tree cover from (a) observations (DeFries and Hansen, 2009) and as simulated by LPX-M, LPX-Mv1-nr and LPX-Mv1-rs without (b–d respectively).



**Fig. 9.** Annual average burnt area between 1997–2005 based on observations from (a) Global Fire Database version 3 (GFED3: Giglio et al., 2010); and (b) version 4 (GFED4: Giglio et al., 2013); (c) southeastern Australia ground observations (Bradstock et al., 2013); and as simulated by (d) LPX; (e) LPX-Mv1-nr; (f) LPX-Mv1-rs.



**Fig. 10.** The difference in (a) tree cover and (b) burnt area between the non-resprouting (LPX-MV1-nr) and resprouting (LPX-Mv1-rs) versions of LPX.