22nd International Congress on Modelling and Simulation, Hobart, Tasmania, Australia, 3 to 8 December 2017
mssanz.org.au/modsim2017

Exploring the future of fuel loads in Tasmania. Shifts in vegetation in response to changing fire weather, productivity, and fire frequency.

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Abstract: Vegetation mediates the interaction between fire and climate, since one of the key determinants of fire activity is the available fuel load. The fuel load is influenced by the structure and composition of the vegetation community, fuel age, rates of decomposition, and vegetation growth rates. Attempts to project future fire danger must therefore account for changes in vegetation growth and fuel dynamics under future climatic conditions.

Estimating fuel load under future conditions is complicated by the interactions that exist between the fire regime, vegetation, climate and human intervention. Feedbacks between these factors can lead to changes in the vegetation, which in turn influence the fire regime. Changes to the frequency of fire due to management decisions (eg. Prescribed burning or fire suppression) and climate change have the potential to affect the flammability of the vegetation, with long term effects on the vegetation structure and composition. Frequent fire in some vegetation types can lead to transformational change when a threshold is crossed, beyond which the vegetation type is radically altered, and this is not always a gradual process. These represent major challenges to projecting fuel loads under future climatic conditions.

However, it is possible to project several important factors determining fire activity into the future. In Tasmania, values for future climate conditions, including fire weather, Soil Dryness Index and productivity are available from a dynamically downscaled climate model (the Climate Futures for Tasmania projections). For other ecological factors, general trends can be estimated (e.g. growth rate, time to maturity), allowing potential pathways of change to be identified, starting with the current flammability and sensitivity to fire of broad vegetation types.

Prescribed burning regimes are likely to change in the future, in response to shifts in community attitudes (eg. With increased concerns about the health effects of smoke), resourcing, and/or a narrowing window available for burning. For this reason, it is important to explore future potential fire activity under different scenarios of fire frequency. We identify the main drivers of change to potential fire activity under future climate change in Tasmania, and explore potential pathways of change to broad vegetation types affecting flammability across the landscape. We use a "pathway modelling" approach to consider multiple transitional pathways that may occur under different fire frequencies. The model is not a predictive model of vegetation flammability or spread under future conditions. Rather, it is a tool to illustrate the potential impacts of climate change (described here using the Climate Futures for Tasmania projections), in combination with the influence of management decisions about frequency of prescribed burning. Within the model, ecological theory is translated into visualizations and summaries of potential landscape-scale change, enabling the impact of fire frequency on vegetation type and potential future fire activity to be considered.

The pathway approach could be used as a tool in community adaptation, to frame potential futures, and identify the consequences of decisions seeking to manage fire risk in the future. Change over time, under different management regimes (frequency of prescribed burning), can be spatially represented to show the shifts in vegetation type, and hence flammability, across Tasmania.

***Keywords*:** *Adaptation, climate change, Climate Futures for Tasmania projections, prescribed burning, TasVeg, vegetation*

1. INTRODUCTION

One of the key determinants of fire activity is the available fuel load. The fuel load is influenced at the landscape scale by community structure and composition (e.g. grassland vs forest), and at more local scales by fuel age, structure and composition; rates of decomposition, which affect the litter depth, structure and composition; and vegetation growth rates. Attempts to project future fire danger must therefore account for changes in vegetation growth and fuel dynamics under future climatic conditions. The challenges associated with quantifying these processes have been identified as a significant gap that limits our ability to project future fire danger (Harris et al. 2016).

Estimating fuel load under future conditions is complicated by the interactions that exist between the fire regime, vegetation, climate and human intervention. Feedbacks between these factors can lead to changes in the vegetation, which in turn influence the fire regime. However, while there are major impediments to projecting fuel loads under future climatic conditions, it is possible to project several important factors determining fire activity into the future. In Tasmania, high resolution values for future climate conditions, including fire weather, Soil Dryness Index and productivity, are available from a dynamically downscaled climate model (the Climate Futures for Tasmania projections (Corney et al. 2010)). For other ecological factors, the general trends can be estimated (e.g. growth rate, time to maturity), allowing potential pathways of change to be identified, starting with the current flammability and sensitivity to fire of broad vegetation types.

The frequency of fire is an important aspect of the fire regime. Changes to the frequency of fire due to management decisions and climate change have the potential to affect the flammability of the vegetation, with long term effects on the vegetation structure and composition. Frequent fire in some vegetation types can lead to transformational change when a threshold is crossed, beyond which the vegetation type is radically altered, and this is not always a gradual process. For example, in forests dominated by obligate seeders, increased frequency of intense fire can cause a state change from woodland to grassland (Bowman et al. 2014). In Tasmania, changes to anthropogenic burning have caused rainforest to shift to moorland and vice-versa (Fletcher and Thomas 2010, di Folco and Kirkpatrick 2013). An increase in the frequency of prescribed burning may also increase fl An increa in some vegetation types. In subalpine and alpine forests of south-eastern Australia, for example, Zylstra (2013) demonstrated that frequent burning (up to a 14-year cycle) led to changes in forest structure that more than doubled the average size of fiemo, which spread faster and were more difficult to suppress.

Prescribed burning regimes are likely to change in the future in response to changes in resourcing, a narrowing window available for burning, and/or shifts in community attitudes due to concerns about fire danger or the health effects of smoke (Johnston and Bowman 2014, Fox–Hughes et al. 2015). For this reason, we explore future potential fire activity under different scenarios of fire frequency. We identify the main drivers of change to potential fire activity under future climate change in Tasmania, and explore potential pathways of change to broad vegetation types affecting flammability across the landscape. We use a "pathway modelling" approach to consider multiple transitional pathways that may occur under different fire frequencies. While the model involves a considerable simplification of the real world of vegetation and fire at the landscape scale, the approach enables a range of plausible futures to be explored, and provides a framework for considering the vegetation responses and feedbacks that may occur between fuel loads and fire weather in the future. It is not intended as a predictive model of vegetation flammability or spread under future conditions. Rather, it is a tool to explore the range of plausible futures arising from a changing climate, in combination with changes to the fire regime due to management decisions.

2. METHODS

2.1. Representing the response to fire of Tasmanian vegetation communities

TasVeg 3.0 (DPIPWE, 2013) provides a map of the Tasmanian vegetation at a resolution of 1:25 000, with 158 mapping units, representing distinct vegetation communities. Associated with each mapping unit is information about the composition, structure and floristics (Harris and Kitchener 2005), from which flammability and fire sensitivity categories have been derived based on the attributes of the common plant species (Pyrke and Marsden-Smedley 2005). There are 24 fire-attribute categories representing vegetation types with similar fire sensitivity and flammability characteristics. There are five fire sensitivity categories (low, moderate, high, very high and extreme) which reflect the potential ecological impact of a single fire on a stand of vegetation. Sensitivity to fire will determine the response of the vegetation to fire, or alternatively, its resilience to frequent burning. Sensitivity is influenced by the reproductive strategy of the dominant species (e.g. obligate seeders vs resprouters, time to maturity). There are four flammability categories (low, moderate, high and very high), based on how many days per year the vegetation type will burn, as indicated by the dynamics of fuel dryness for that vegetation type (more details in Pyrke & Marsden-Smedley, 2005). These attributes were considered when grouping vegetation types into 8 'vegetation pathways' and 64 broad vegetation types that act as steps along each pathway. The vegetation types, pathways and the TasVeg 3.0 VEGCODEs are presented in Table 1. As the vegetation types are quite broad from an ecological point of view, vegetation type and fire sensitivity are treated separately, and allowed to evolve independently.

Table 1. The vegetation 'pathways' followed in the model. The order of the vegetation types reflects the pathway followed in the model. The associated TasVeg 3.0 VEGCODEs represent the original vegetation types used to develop the pathways.

Broad Vegetation Type	Pathway	Tas Veg 3.0 VEGCODE
Buttongrass	Buttongrass moorland woodland shrubby or heathy understorey; Buttongrass moorland; Buttongrass moorland bare ground	MBE; MBP; MBR; MBS; MBU; MBW; MRR; MSW
Generic	Generic forest; Generic dry scrub; Generic woodland shrubby or heathy understorey; Generic woodland grassy understorey; Generic grassland; Generic bare ground; Generic heathland; Generic heathland grassland; Generic heathland bare ground;	NBA; SAL; SCA; SED; SLS; SMP; SSC; SKA; GCL; GHC; GPH; GPL; GRP; GTL; SCH; SHW; SLG; SRH; SSZ; SCL; DBA; DGW; DMW; DVG; DOW; DKW; DPD; DPO
Eucalypt	Eucalypt wet sclerophyll forest with rainforest understorey; Eucalypt wet sclerophyll forest broadleaf tree understorey; Eucalypt wet sclerophyll forest with shrubby or heathy understorey; Eucalypt dry sclerophyll forest shrubby understorey; Eucalypt dry sclerophyll forest shrubby or heathy or broadleaf understorey; Eucalypt dry sclerophyll forest shrubby or heathy or buttongrass understorey; Eucalypt dry sclerophyll forest shrubby or heathy or grassy understorey; Eucalypt dry sclerophyll forest shrubby or heathy understorey; Eucalypt dry sclerophyll forest shrubby or grassy understorey; Eucalypt dry sclerophyll forest heathy understorey; Eucalypt dry sclerophyll forest grassy understorey; Eucalypt woodland shrubby or heathy understorey; Eucalypt woodland grassy understorey; Eucalypt grassland; Eucalypt bare ground	DGL; DTO; DAC; DNI; DAM; DSG; DSO; DTD; DTG; DDE; DOV; DPU; DRI; DRO; DAS; DOB; DVC; DSC; DNF; DAD; WDB; WOB; WVI; WDA; WDL; WNL; WOL; WRE; WSU; WDU; WOU; WNU; WBR; WDR; WGK; WNR; WOR
Non-Eucalypt	Non-eucalypt wet forest broadleaf understorey; Non-eucalypt wet forest shrubby or broadleaf understorey; Non-eucalypt wet forest shrubby understorey; Non-eucalypt wet forest heathy understorey; Non-eucalypt wet forest sedgey understorey; Non-eucalypt wet scrub shrubby understorey; Non-eucalypt wet scrub heathy understorey; Non-eucalypt wet scrub sedgey understorey; Non-eucalypt dry forest; Non-eucalypt dry scrub; Non-eucalypt heathland; Non-eucalypt grassland; Non-eucalypt bare ground	NRL; NRV; NCR; NRR; NRD; NLM; NRF; NME; NBS; NLA; SBM; NLE; SSK; SWR; SBR; SRE; SLL; SLW; SMM; SMR; SWW
Sphagnum	Sphagnum; Sphagnum sedgeland; Sphagnum bare ground	GSL; MSP
Rainforest	Rainforest with conifers or deciduous beech; Rainforest without conifers or deciduous beech; Rainforest wet scrub shrubby understorey; Rainforest wet scrub heathy understorey; Rainforest wet scrub sedgey understorey; Rainforest heathland; Rainforest sedgeland; Rainforest grassland; Rainforest bare ground	RHP; RKF; RKP; RKX; RMU; RMT; RCO; RFE; RML; RMS; RSH; SRF
Subalpine	Subalpine rainforest; Subalpine scrub; Subalpine woodland; Subalpine heathland; Subalpine sedgeland; Subalpine grassland; Subalpine bare ground	DCO; RKS; SHS; RPF; RPP; SSW; DDP; NLN; RPW
Alpine	Alpine heathland with conifers; Alpine heathland without conifers; Alpine rushland or sedgeland; Alpine bare ground	HUE; HCH; RFS; HCM; HHE; HHW; HSE; HSW; MDS; MGH

2.2. Vegetation pathways through time

The model starts with a broad vegetation type which determines the pathway, but the rate at which change occurs is based on the sensitivity and flammability attributes of the underlying mapping units. Baseline composition, structure, flammability and fire sensitivity of vegetation types were taken from TasVeg 3.0. Transitional gradients, from wet forest types through to dry forests, woodlands and grasslands, are followed, dependent on the fire frequency. Different understorey types within the broad vegetation types reflect the fertility of the site, moisture and fire history and influence the rate of change. Eucalyptus forests, Non-eucalyptus forests and Rainforests follow different pathways, represented by a gradient of moisture and fire frequency. Subalpine and Alpine types are treated separately to reflect their higher sensitivities to fire. The pathways can be reversed under fire suppression scenarios except where site factors determine the present vegetation type. For example, grassland can move towards forest if fire is suppressed, and non-eucalypt wet forest may become drier in the future and with increased fire frequency. However, dry non-eucalypt forests cannot become wet forests because the current composition reflects the moisture of the site (e.g. *Allocasuarina* occurs on dry sites, *Acacia* on wet sites). Fire sensitivity was changed at each time step to reflect any changes to vegetation type, based on the assumption that the vegetation community will shift in the direction of lower fire sensitivity (ie. more fire adapted) if the inter-fire interval is shorter than the interval that the original community requires to maintain the defining species. For example, a vegetation type in the Extreme category moves one step to the Very High category if the inter-fire interval is less than 500 years, because any fire will cause either irreversible or very long-term (> 500 years) damage. A fire-adapted community with Moderate fire sensitivity will move one step to the Low category if the inter-fire interval is less than 15 years, and remain at Moderate if the inter-fire interval is greater than 15 years, because vegetation communities in this category require at least 15 years between fires to maintain the defining species. Conversely, a Grassland with Low fire sensitivity can move in the other direction if fire is excluded for more than 100 years, as the community shifts towards a more mesic vegetation type. Flammability was also updated at each time step to reflect any changes to vegetation type.

2.3. Modelling Potential Fire Activity

The Potential Fire Activity index (PFA) is based on the four switch model (Bradstock 2010), which describes fire activity in terms of four factors that must be fulfilled simultaneously (switched "on") for fire to occur. There must be fuel available (biomass); it must be dry enough to burn (availability to burn); weather conditions must be conducive to fire spread (fire weather), and there must be an ignition source (ignition). We define the "Potential fire activity" as the level of fire activity possible if an ignition source were present. The layers used to calculate each of these elements, and their relationship to each other, are summarized in Table 2 and Figure 1. Other attributes were initialized from TasVeg 3.0 and then evolved along the vegetation pathways. Modelling PFA is a two-step process. First, the broad vegetation type is determined for each cell for a particular time and inter-fire interval. Then, the PFA is calculated using the appropriate attributes for that type, following the equation:

Potential Fire Activity = Biomass + Availability to burn + Fire Weather

where: Biomass = Productivity * Fuel load at time since fire

Availability to burn = Flammability of Vegetation Type at current SDI * Slope factor

Fire Weather = Fire Danger Index [#]

[#] FFDI or MFDI depending on the vegetation type.

PFA was calculated at each grid cell (10km) across Tasmania for seven time periods (1961–1980, 1981-2000, 2001-2020, 2021-2040, 2041–2060, 2061-2080, 2081–2100). Climate indices used in the equation reflect the appropriate time period, so if the model is 50 years from 2000, then the climate layer at that time step is 2040-2060. Soil Dryness Index (SDI) (Mount, 1972); Forest Fire Danger Index (FFDI) (McArthur, 1967); and Moorland Fire Danger Index (MFDI) (Marsden-Smedley et al. 1999) were calculated from the Climate Futures for Tasmania projections. Maximum values for the time period were used to emulate worst case conditions.

2.4. Fire Frequency

We explored the effect of different fire frequencies on the potential fire activity and flammability of vegetation across Tasmania. The climate driven layers (productivity, SDI and fire weather) were updated to reflect the changing climate over time, and the vegetation type was shifted along the appropriate pathway when the fire frequency was above the threshold for each type. Values for the time between fires (inter-fire interval) required for recovery were based on available literature.

3. RESULTS AND DISCUSSION

Future fire danger is projected to increase substantially under ongoing climate change (Fox-Hughes et al. 2014). More frequent bushfires can therefore be expected, leading to a greater need for prescribed burning to reduce bushfire risks. A trade-off may arise between fuel reduction, flammability and vegetation transitions in response to more frequent fire. The vegetation pathway model is a tool to illustrate the potential impacts of a dryer and warmer future climate in combination with management decisions about frequency of prescribed burning.

3.1 Impact of fire frequency on vegetation type

Frequent fire has the potential to lead to shifts in vegetation type, away from mesic, fire sensitive types, towards drier, more fire adapted vegetation. The rate of change differs across the vegetation types, with some fire sensitive communities irreversibly impacted by even a single fire, and requiring very long recovery times. For example, rainforest communities with conifers may never recover after a fire, as *Athrotaxis* is an extremely slow growing and very long-lived tree that is killed by fire. In such communities there is a positive feedback where fires promote vegetation that is more flammable, increasing the risk of fire. In contrast, fire-adapted vegetation such as dry eucalypt forests, recover relatively quickly after fire, and are only impacted by very frequent fires. This can be illustrated in several ways. A map can be used to show the distribution of the vegetation types, and how this changes at different inter-fire intervals. Here we show the impact of very frequent fire, but any interval of interest could be investigated. At a statewide level, very frequent fire, with only 4 years between fires, results in a shift towards drier vegetation types across the state (Figure 2A).

Table 2. Layers used to calculate Potential Fire Activity (PFA) at current and future time periods

Switch	Component terms	Layers used in calculation
Biomass	Productivity	An index of relative potential plant growth, based on three different plant growth responses to light, temperature and water regimes under current and future climate conditions, calculated using the GROCLIM sub-model from the ANUCLIM model (Hutchinson 2011).
	Fuel load at time since fire	Biomass (of fuel) = L*(1-exp(-k*A)), where: L = carrying capacity; k = growth rate; A = age (or time since fire). Values for each vegetation type chosen after consultation with the literature and fire ecologists.
Availability to burn	Flammability of Vegetation Type at current SDI	Four flammability categories (low, moderate, high and very high) based on how many days per year the vegetation type will burn, as indicated by the dynamics of fuel dryness for that vegetation type (adapted from Marsden-Smedley et al. 1999).
	Slope factor	Slope correction factor to incorporate the effect on fuel pre-heating and wind speed. Slopes > 31% weighted by 10; slopes 21-30% by 5; slopes 16-20% by 3; slopes 0- 10% were weighted by 1.
Fire Weather	Moorland Fire Danger Index (MFDI)	MFDI (Marsden-Smedley et al. 1999) for areas with Buttongrass Moorland, Sphagnum and Sedgeland vegetation.
	Forest Fire Danger Index (FFDI)	FFDI (Noble et al. 1980) for all other vegetation types. Both indices incorporate surface air temperature, relative humidity and wind speed, combined with an estimate of fuel dryness (Drought Factor, based on Soil Driness Index (SDI) and recent precipitation).

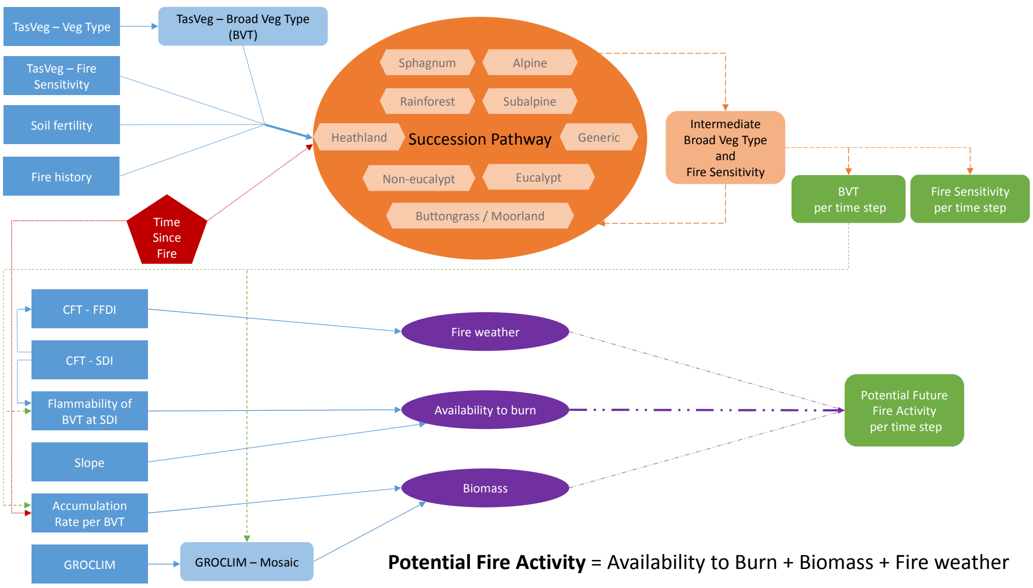

Figure 1. The components of the vegetation pathway model. Blue boxes are inputs. Light-blue boxes are derived products. Orange components represent the different vegetation pathways followed over time. Purple boxes represent the “switches” calculated. Green boxes are useful outputs in their own right. ‘Broad Vegetation Type per timestep’ is used to define the vegetation conditions and estimate the Potential Fire Activity at each timestep.

Regions with fire sensitive vegetation are highlighted, as the vegetation shifts quickly at high fire frequency. For example, the wet sclerophyll forests with rainforest or broadleaved understoreys in southern Tasmania (shown in orange) quickly move towards dry forest types. In contrast, at very long inter-fire intervals (or low fire frequency), which would occur if fire were actively suppressed, some vegetation types could potentially transition towards different vegetation types (not shown here). For instance, if fire were suppressed in native grasslands, there would be a shift towards woodland vegetation as trees establish in the absence of frequent fire. Buttongrass moorland transitions to a woody vegetation type if fire is suppressed and the inter-fire interval is longer than 30 years. The regions with the most fire sensitive vegetation types and therefore greatest potential for vegetation transitions can be highlighted in this way. The transitions along each pathway with an inter-fire interval of 10 years is presented in Figure 2B. This highlights how the dry eucalpyt forests and woodland types in which prescribed burning is currently carried out are sustained at a ten-year inter-fire interval, whereas alpine, subalpine and rainforest types would be lost.

Alternatively, the impact of fire frequency can be demonstrated by comparing the area of Tasmania covered by different vegetation types (e.g. grassland vs woodland) over time under different frequencies of fire (Figure 2C). The bare ground category is used when the vegetation has been pushed beyond the limits of adaptability, and no vegetation is able to establish. If fires were to occur every two years for a period of 15 years, only grasslands and dry forests would remain, and many areas, such as alpine areas and sphagnum, would become bare ground.

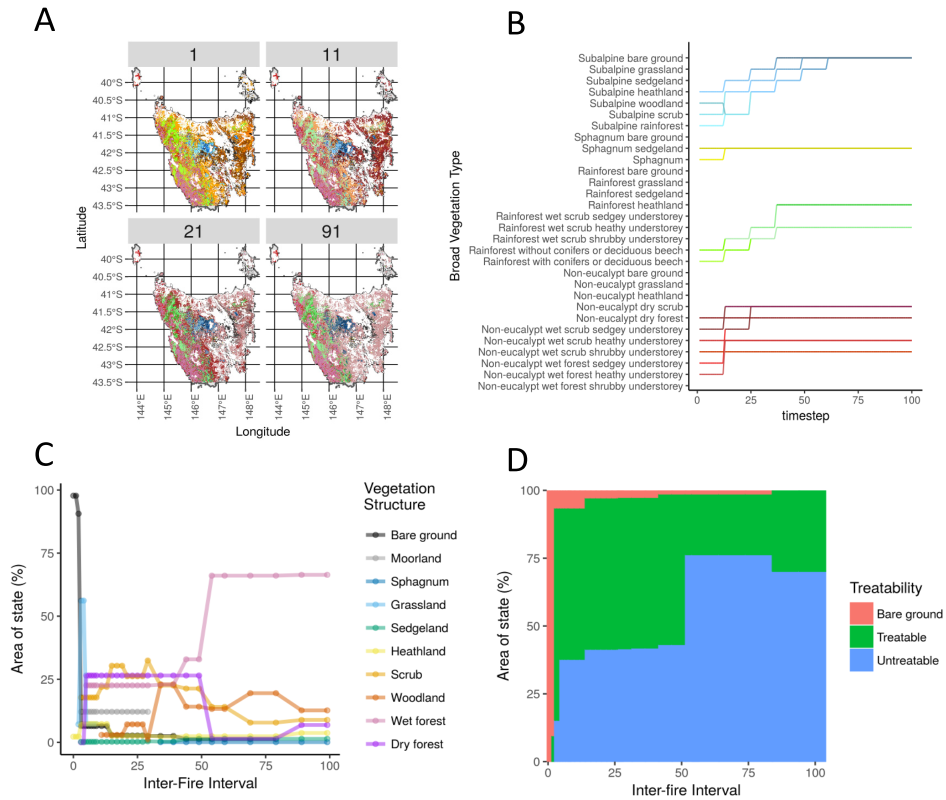

Figure 2. Indicative model output visualizations. **A)** Impact of frequent fire (every 4 years) across Tasmania. The numbers above each map refer to the number of years since 2000. Colours represent different vegetation types. **B)** The impact of a ten-year inter-fire interval on vegetation type across Tasmania over a period of 100 years, beginning in 2000. Demonstrates how transitions were constrained along vegetation pathways, with each type having different tolerances to fire frequency. **C)** The difference in the area of Tasmania covered by different vegetation structural types after 100 years of burns at a range of inter-fire intervals. **D)** The impact of various inter-fire intervals on the treatability of vegetation across the state. At high frequency return rates, treatable vegetation is transformed into bare ground. At low frequency burn rates, treatable vegetation transitions into untreatable types.

As the inter-fire interval increases (e.g. to seven years), there is less of an impact on the fire-adapted vegetation types such as grasslands and woodlands, but there is still an increase in their area as the more mesic vegetation types transitions towards grassland and woodland. The area of forest appears stable at these fire frequencies, but there is a shift towards dry forest, away from wet eucalypt and non-eucalypt forests. The current area of woodlands can be sustained into the future at inter-fire intervals above 16 years. At longer intervals, the area increases, as grasslands transition into woodlands when fire is suppressed. Untreatable vegetation types, such as alpine and subalpine heathland and grasslands and rainforest, are excluded from fuel management because their sensitivity to fire would result in the loss of fire-sensitive species and long-term changes to their composition. Change in vegetation type across the landscape therefore affects the percent treatability across Tasmania (Figure 2D), with consequences for planning and resourcing in the future.

3.2 Impact of inter-fire interval on Potential Future Fire Activity

Fire frequency has a substantial impact on the Potential Fire Activity (PFA) relative to the impact of the changing climate over the coming decades. Although it is expected that transitions towards drier vegetation types have important consequences for the PFA because of the link with flammability in drier, fire adapted vegetation types, the model configuration at present is weighted towards the total potential fuel available for each vegetation type. So from this perspective, bare ground and grasslands have significantly lower PFA than forests of any kind. With very high fire frequency (inter-fire interval of 1-2 years), the PFA is very low because all vegetation is pushed towards the bare ground state over time in the model. Beyond 3 yearly intervals, the more frequent the fire, the lower distribution and the peak of the state-wide PFA. The highest PFA values are all inter-fire intervals greater than 30 years, reflecting the contribution of fuel accumulation and carrying capacity to fire activity. Future model iterations plan to improve the importance of flammability relative to total fuel volume to better reflect expert knowledge in this area.

4. CONCLUSIONS

The frequency and intensity of prescribed burning impacts vegetation composition and structure across the landscape. The pathway model consolidates current understanding in the field into an interactive framework, enabling plausible futures to be explored. It could be used as a tool in community adaptation, to frame potential futures, and identify the consequences of decisions seeking to manage fire risk in the future. Change over time, under different management regimes (frequency of prescribed burning), can be spatially represented to show the shifts in vegetation types across the landscape. Further development of the model would benefit from research into fuel accumulation, flammability and fire intensity, and potential changes to the distribution of species and vegetation communities as a result of changing climate conditions in the future.

ACKNOWLEDGMENTS

This work was funded by the National Bushfire Mitigation – Tasmanian Grants Program (NBMP). Workshop participants from the Tasmania Fire Service, Tasmanian Parks and Wildlife Service, Forestry Tasmania, DPIPWE and the University of Tasmania contributed valuable knowledge to the development of the model.

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