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Flammability dynamics in the Australian Alps

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Abstract

Forests of the Australian Alps (SE Australia) are considered some of the most vulnerable to climate change in the country, with ecosystem collapse considered likely for some due to frequent fire. It is not yet known, however, whether increasing fire frequency may stabilize due to reductions in flammability related to reduced time for fuel accumulation, show no trend, or increase due to positive feedbacks related to vegetation changes. To determine what these trends have been historically, dynamics were measured for 58 years of mapped fire history. The 1.4 million ha forested area was divided into broad formations based on structure and dominant canopy trees, and dynamics were measured for each using flammability ratio, a modification of probability of ignition at a point. Crown fire likelihood was measured for each formation, based on satellite-derived measurements of the 2003 fire effects across a large part of the area. Contrary to popular perception but consistent with mechanistic expectations, all forests exhibited pronounced positive feedbacks. The strongest response was observed in tall, wet forests dominated by Ash-type eucalypts, where, despite a short period of low flammability following fire, post-disturbance stands have been more than eight times as likely to burn than have mature stands. The weakest feedbacks occurred in open forest, although post-disturbance forests were still 1.5 times as likely to burn as mature forests. Apart from low, dry open woodland where there was insufficient data to detect a trend, all forests were most likely to experience crown fire during their period of regeneration. The implications of this are significant for the Alps, as increasing fire frequency has the potential to accelerate by producing an increasingly flammable landscape. These effects may be semi-permanent in tall, wet forest, where frequent fire promotes ecosystem collapse into either the more flammable open forest formation, or to heathland.

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Abstract

Forests of the Australian Alps (SE Australia) are considered some of the most vulnerable to climate change in the country, with ecosystem collapse considered likely for some due to frequent fire. It is not yet known, however, whether increasing fire frequency may stabilise due to reductions in flammability related to fuel accumulation, show no trend, or increase due to positive feedbacks related to vegetation changes. To determine what these trends have been historically, dynamics were measured for 58 years of mapped fire history. The 1.4 million ha forested area was divided into five broad formations based on structure and dominant canopy trees, and dynamics were measured for each using Probability of Ignition at a Point, modified to minimise noise from small outliers. Crown fire likelihood was measured for each formation, based on satellite-derived measurements of the 2003 fire effects across the NSW and ACT Alps. Contrary to popular perception but consistent with mechanistic expectations, all forests exhibited pronounced positive feedbacks. The strongest response was observed in tall, wet forests (TWF) dominated by Ash-type eucalypts, where despite a short period of low flammability following fire, regenerating stands have been more than eight times as likely to burn than have mature stands. The weakest feedbacks occurred in open forest (OF), although regenerating forests were still 1.5 times as likely to burn as mature forests. Aside from low, dry open woodland where there was insufficient data to detect a trend, all forests were most likely to experience crown fire during their period of regeneration. The implications of this are significant for the Alps, as increasing fire frequency has the potential to accelerate by producing an increasingly flammable landscape. These effects may be semi-permanent in TWF, where frequent fire promotes ecosystem collapse into either the more flammable OF formation, or to heathland.

Key-words Australian Alps, climate change impacts, ecosystem collapse, flammability

INTRODUCTION

The fire season is both lengthening and becoming more severe in Australia, in line with global trends (Jolly *et al.* 2015; Flannigan *et al.* 2013; Clarke *et al.* 2013). Coupled with the increase in lightning activity (Reeve and Toumi 1999), this has the potential to greatly increase the impact of fire on forest and other ecosystems (Krause *et al.* 2014) through 'interval squeeze' (Enright *et al.* 2015), with consequent feedbacks into the carbon cycle (e.g. (Fisher *et al.* 2016)). Although much of the focus of this impact has gone to climate; the flammability dynamics of ecosystems may play a comparable role. These have the capacity to either reduce or amplify the effect of external drivers, yet they are poorly understood, and our lack of knowledge in this area represents a major barrier to understanding the earth system (Harris *et al.* 2016).

If regenerating forests are on average less flammable than mature forest, the system remains stable when external drivers increase fire frequency, because those pressures are balanced by reduced flammability (negative feedback). Conversely, where the feedback is positive and regenerating forest is on average more flammable than mature forest, the frequency and/or severity of fire is amplified. This makes the ecosystem more vulnerable to collapse (Keith *et al.* 2013; Lindenmayer *et al.* 2011), while increasing the threat to human values. Positive feedbacks therefore have the potential to cause tipping points in both the likelihood and consequence components of wildfire risk.

The Australian Alps

The Australian Alps require consideration in this regard, as they are vulnerable to both bioclimatic and abiotic changes, and as an 'elevationally restricted mountain ecosystem' they fall into the category of first concern for Australian ecosystems at risk from climate change

(Laurance *et al.* 2011). Using the criteria of this panel, the susceptibility of the Australian Alps is increased by the dependence of some montane and subalpine forests on cloud-stripping for moisture inputs (Costin 1961), the declining seasonal snow cover of the mountains (Sánchez-Bayo and Green 2013; Davis 2013), and their value as habitat to high numbers of restricted endemic species (Pickering *et al.* 2004). The alpine area is of particular concern in this regard (Hughes 2010).

As described earlier, fire can operate to amplify change through feedbacks between changing fire regimes and landscape flammability. In the montane zone, (Bowman *et al.* 2014) have measured localised ecosystem collapses produced by fire in tall, obligate-seeding Alpine Ash (*Eucalyptus delegatensis* subsp. *delegatensis*, Myrtaceae) forests. Although the likelihood of total ecosystem collapse has not yet been measured for these forests, there is significant risk of total collapse for some alpine communities such as snow patch herbfield or feldmark (Green and Pickering 2009; Williams *et al.* 2015). The risk of this occurring due to shrub encroachment was considered greater under changed fire regimes, and increases in fire frequency are likely not only because of the changing climate, but are amplified by the positive feedbacks in the surrounding alpine (Camac *et al.* 2017) and lower sub-alpine communities (Zylstra 2013) through which fire generally enters the alpine area. Fire can also act as a catalyst for climate-driven change along ecotones between formations, as observed in Yellowstone National Park (Donato *et al.* 2016). The strength and direction of feedbacks in the wider forested area of the Alps may then be critical in either mitigating this risk by providing a buffer that loses flammability when fire becomes more frequent, or compounds it by increasing landscape connectivity and fire contagion as they are burnt more often.

Defining flammability

Such concerns however may for some be counterintuitive in Australian eucalypt forests, which are frequently described as ‘fire adapted’, with arguments for deliberate management increases in fire frequency coming from both political and some academic sources (Attiwill and Adams 2013; Baker and Catterall 2016; Teague *et al.* 2010). While debate continues over the ecological veracity of this characterisation (Bradshaw *et al.* 2011), care is needed that ecological requirements do not become conflated with plant or stand flammability trends.

The concept of flammability is frequently misunderstood or poorly applied, and this is largely due to the lack of clear definition and objective units of measurement. At the heart of this is the reality that the three components of ignitability, combustibility and sustainability operate either independently or as counter-measures to each other (Gill and Zylstra 2005). A fuel that burns quickly for example is highly combustible, but has low sustainability. As illustrated in (Zylstra *et al.* 2016), if other factors are equal, a thin leaf is more readily ignitable than a thick one, but has lower sustainability. If a plant is composed from thin leaves however, it is more likely that ignition will spread through it rapidly, which may result in a more combustible plant; or in a less combustible one if some burning leaves expire before the rest of the plant ignites. One level of flammability therefore emerges from its components, so that measures are not readily scalable and it is not valid to say that a plant or an ecosystem is more or less flammable due to measured components, unless that complexity is modelled. Some of this ambiguity in plant flammability was succinctly captured in the “non-flammable, the fast-flammable and the hot-flammable” categories described by (Pausas *et al.* 2017).

Reference to flammability at the scale of a stand, an ecosystem or a landscape then has the potential to become meaningless. Tall forests can at times burn with extraordinary intensity, so that the word "flammable" appears an apt description. But if this has a natural return interval of centuries, can it objectively be considered more or less flammable than the grassland that burns every few years? Such questions emphasise the need to reference flammability as both an emergent, and relative property of the ecosystem. Emergent because of the complexity producing the behaviour (Zylstra 2011), and relative because its definition depends on the way that fire relates to the components of the ecosystem. The difference between two different fire behaviours is only of importance to a life if one of those behaviours will not harm it; otherwise the distinction loses significance. This is expressed in the consideration of flammability as a biological concept (Pausas and Moreira 2012), where it is measured relative to the influence that resultant flames exert in niche construction, population dynamics, and other evolutionary and ecological mechanisms. This can be quantified for a point using measures of severity, and for a landscape, using Probability of Ignition at a Point (PIP, e.g. (Gill *et al.* 2000; de Ligt 2005)). In risk terms, these express consequence and likelihood.

Aims

In order to better define the risk posed to the Australian Alps through fire, the aim of this paper is to quantify the fire-flammability feedbacks across all broad forest formations of the Australian Alps.

MATERIALS AND METHODS

Location

The study was conducted in the forested part of the Australian Alps bioregion contained within the Australian Alps National Parks. This covers 1.4m ha across the states of New South Wales and Victoria along with the Australian Capital Territory.

The environment is highly diverse, largely due to topography. Elevation ranges from close to sea level in the south east, to the highest forested areas in Australia at 1960m.a.s.l., and the area spans two temperate climatic divisions with distinctly dry summers ranging from mild to hot (Stern *et al.* 2000). Mean annual rainfall ranges from 500mm to over 2300mm, and snow can persist for up to six months in areas above 1400m.a.s.l. (NSW Office of Environment and Heritage 2016; Clayton-Greene and Ashton 1990). Pre-European fire return-intervals ranged from multiple decades to centuries (Zylstra 2006).

Forests were broadly grouped in formations divided by structure (Specht 1970) and dominant tree species, combining units from Victorian Ecological Vegetation Groups (Department of Sustainability and Environment 2010) and NSW/ACT Formations (Gellie 2005). Mapping is not consistent between the two systems, but the formations shared the same dominant canopy species, and mapped patches matched reasonably well where they bordered. These formed one tall wet forest (TWF), one open forest (OF), one subalpine open forest-woodland (SFW), one dry open forest (DOF), and one low, dry open woodland (LDOW, Table 1, Fig. 1). Of these, previous analysis has demonstrated positive feedbacks in SFW (Zylstra 2013, 2016) and the *Eucalyptus regnans* (Myrtaceae) component of TWF (Taylor *et al.* 2014). Consistent with increases in local fire weather severity (Clarke *et al.* 2013), fire frequency in the study area has increased sharply in the 21st century (Fairman *et al.* 2016). As a result, much of this formation is expected to be lost over the remainder of this century (Bowman *et al.* 2014; Ferguson 2010). No feedbacks have been quantified for the remaining area.

INSERT FIG. 1 AROUND HERE

Fire History

The primary data used for all fires mapped for the 58 years from 1957 to 2015 were records sourced from State Government agencies (New South Wales Office of Environment and Heritage, Australian Capital Territory Emergency Services Agency, and the Victorian Department of Environment and Primary Industries, unpublished data). These were checked for duplicate polygons, and fires that had not been entered from the archived paper records were added to the dataset from that used by (Zylstra 2013). Some fires had been mapped prior to this period, however the quality and frequency of this was inconsistent, rendering the data too poor for analysis.

Analysis 1: Flammability feedbacks

Flammability feedbacks were determined by relating time since fire to two measures of Probability of Ignition at a Point (PIP) – probability of a cell burning, and probability of crown fire within a burning cell. The overall feedback was measured from the first of these, whereas the second was used to provide further insight.

The required inputs for each analysis were collected in ArcGIS (ESRI 2015) from 1ha grid cells, and analysis performed in the R Statistical Environment (R Core Team 2016).

To find the probability of a cell burning, PIP was calculated using Flammability Ratio FR (Zylstra 2013), as this includes a scaling factor to account for noise produced by small age-class samples. Simple PIP is defined as the proportion of a given stand age that is burnt. But if a certain age is only represented by a small pocket, a large fire may easily consume all of it and give a probability of one, regardless of its characteristic flammability. To account for this, FR scales the influence of each fire year on the final statistic by producing the Area

Factor (*AF*, Equation 1), which is the standard PIP (left hand term) multiplied by the ratio of average age class area $\bar{x}A$ to total burnt area Σ_b (right hand term). Years in which the area of fire is large compared to the average age class area are scaled down in influence, and those years where fires are smaller are given greater influence.

$$AF = \frac{A_b}{A} \cdot \frac{\bar{x}A}{\Sigma_b}$$

Equation 1.

Where A_b is the area of the age class burnt, and A is the total area of that age class.

FR for a given age and year is equal to the *AF* divided by the average of all *AF* values across all ages and years, and the FR for that age across all years is the average of all FR values collected for that age.

In keeping with (McCarthy *et al.* 2001) and the introductory comments on flammability, FR incorporates the term in preference to 'hazard' or 'probability', as the probability of ignition at a point represents both an emergent and a relative outcome. In a landscape such as the Alps, where fire is actively suppressed, there is greater probability of a point burning if fires not only spread faster, but are more difficult to suppress due to factors such as larger flames and / or more spot fires over greater distances. These behaviours are all aspects of flammability at a landscape level (Gill and Zylstra 2005), and FR combines them into the single emergent feature of measured burnt area.

Spatial autocorrelation is likely within a given year, as fire burns discrete patches rather than random locations. This can however be disregarded when multiple years are examined, as new patches are formed in each year.

Analysis 2: Likelihood of crown fire ignition

To find the likelihood of crown fire L_{cb} in any burning cell, crown fire measurements were made from difference Normalised Burn Ratio dNBR (e.g. (Keeley 2009)), mapped for a 632,448ha subset of the 2003 bushfires in NSW and the ACT (Barrett 2006), using only the highest class of severity to denote crown fire.

As PIP was only measured for a single year, data could not be corrected via the FR, which weights values by comparison between years. The smaller dataset was therefore statistically weaker than that used in the first analysis, due to the possibility of small, highly influential outliers burnt in this very large fire, and to spatial autocorrelation.

To account for noise from small outliers, these were identified using Grubbs test (Grubbs 1950) via the 'outliers' package in R (Komsta 2011), and the largest outlier for each formation was removed if $p < 0.05$ for Grubbs' statistic. To limit the loss to data, a maximum of one outlier constituting less than 0.5% of the area of each formation was removed.

To account for spatial autocorrelation, severity measurements were made using a random grid of cells that covered 75% of each formation.

Fitting functions

In order to find trends in the dynamics, a series of functions were fit to the data using the NLS package for R (Bates and Chambers 1992). Where more than one contender was identified, the best was chosen by comparing the Akaike Information Criterion (AIC (Akaike 1974)) using Akaike weight (Symonds and Moussalli 2011) to give the probability that this was the best approximating model. For the smaller datasets used in the second analysis, AIC_c was used (Symonds and Moussalli 2011).

All dynamics were assumed to commence with a period of low, increasing flammability, where ground fuels are absent immediately following fire. Five functions were used for this purpose (Fig. 2) - the Olsen function ((Olsen 1963), Equation 3) and a logistic function (Equation 4) describe negative feedbacks, however the logistic function allows for a longer period of initial reduced flammability compared to Olsen. The other functions ((Burr 1942), Equation 5), the standard binomial distribution (Equation 6) and the Moisture function (Equation 7, (McCarthy *et al.* 2001)) allow for positive feedbacks; with Burr capable of representing both.

$$FR = a(1 - e^{-b.T})$$

Equation 3

$$FR = \frac{K}{1 + e^{(a - r.T)}}$$

Equation 4

$$FR = ab\frac{0.1T^{a-1}}{(1 + 0.1T^{a})^{b+1}}$$

Equation 5

$$FR = \frac{sc}{s\sqrt{2\pi}} \, . \, e^{\frac{(-T-\bar{x})^2}{2s^2}}$$

Equation 6

$$FR = a(1 - e^{-bT})(c + e^{-dT})$$

Equation 7

Where T is years since the last fire, a to d are constants, r is the biotic rate of increase, K is an asymptote, sc is a scaling factor, s is the standard deviation, and $\bar{x}$ is the mean.

INSERT FIG. 2 AROUND HERE

Models were excluded if they could not be fit using NLS, or if when fit, all constants did not have $p < 0.01$. When this occurred in the FR analysis, outliers were successively identified using Grubbs test (Grubbs 1950; Komsta 2011) and subsequently removed before re-examination. As this dataset was much larger than that used in the second analysis; rather than set an arbitrary limit to the size of outliers, the percentage burnt area that was removed was reported as qualifying data. As already described, the largest outlier in the dataset used for the second analysis was routinely removed, if it constituted less than 0.5% of the formation area.

A model was chosen if it achieved significance, and where more than one did so, if Akaike weight was greater than 0.5. If no model satisfied these criteria, the null hypothesis was not rejected.

In order to best represent the data, any FR model chosen that did not achieve the highest level of significance ($p < 0.001$) was again examined for outliers. If these outliers constituted only a very small part of the burnt study area and did not change support from one alternate hypothesis to another, they were removed until maximum significance was achieved, if that was possible. Again, the area of forest removed as outliers was reported to provide qualification to these models.

Measuring feedbacks

To determine feedbacks in the first analysis, the null hypothesis H_0 of no feedback (i.e., flammability remains constant) was tested against two alternate hypotheses of negative feedback H_1 and positive feedback H_2. Feedbacks were defined from FR, as this provided the most comprehensive measure of flammability. These were termed positive if the average flammability of mature forests was less than the average taken across the whole period of regeneration, negative if mature forests were more flammable, or no feedback if no model could be fit, or if the null model provided the best fit.

Flammability dynamics in the Olsen and logistic models were divided into a young period (Y), in which modelled FR < 1, and a mature period (M) of all ages beyond this. For the other functions where FR dropped below unity at older age classes, Y was calculated, followed by a regrowth period (R) where modelled FR ≥ 1, then a mature period of all ages where FR was once again < 1. The mean FR for each of these periods was measured from the raw data, after the removal of any outliers.

The strength of each feedback was quantified as feedback strength (FS), which is the mean FR for non-mature forest (Y, or Y+R depending on the function) divided by the mean FR for M. Where the feedback was positive, young equivalent (YE) was calculated as the number of years for which the mean modelled flammability of regrowing forests was less than or equal to the mean flammability of mature forests.

For both analyses, the strength of the best model for each community was indicated by residual standard error for the full datasets, and by R^2. For FR, R^2 was measured against mean FR values for each age in preference to raw values, to minimise the noise arising from inter-annual stochastic differences and thereby providing a better representation of the feedback.

Final models

To find the annual likelihood of fire L_f in each age and formation, the relevant FR models were multiplied by the mean likelihood of fire L across the formation being studied (Equation 8).

$$L = \frac{\Sigma_{bY}}{\Sigma_{AY}}$$

Equation 8.

Where Σ_{AY} is the sum of all areas of known age for all years, and Σ_{bY} is the sum of all burnt areas within those known ages, for all years.

To find the annual likelihood of crown fire L_c in each age and formation, the relevant models for likelihood of crown fire in a burning stand L_{cb} were multiplied by L_f.

RESULTS

Flammability feedbacks

Flammability Ratio could be measured for the 52 years following 1964 in all formations except LDOW, where the first fire to burn forest of a known age was in 1965 (Appendix S1).

The only significant models in all formations were Burr and the binomial distribution (Table 2, Fig. 3), with Burr providing the strongest fit of the two in all cases. DOF, SFW, and TWF (Figs. 3a, d and e) all had the highest category of significance for the study (p = 0.0001) when modelled from the full dataset using Burr. OF was significant with the full dataset (p = 0.01), but removal of two outliers constituting 0.007% of the studied burnt area increased this to p = 0.0001 (Fig. 3c). LDOW was only significant if the largest outlier was removed, but removal of another two outliers constituting 0.183% of the burnt area produced a model with p = 0.0001.

INSERT FIG. 3 AROUND HERE

Further outliers were apparent in some formations such as OF, but were not removed if a function had already been fit with the highest category of significance.

Feedback strength was greater than one for all formations, indicating that flammability of regenerating forests was higher than that of mature forests.

Likelihood of crown fire ignition

The number of age classes burnt in 2003 and for which data was available varied between 20 (LDOW) and 40 (TWF), allowing functions to be fit to all formations except for LDOW (Table 3, Appendix S2). The trend was binomial in three cases, and followed a Burr curve for DOF due to a weak trend of more crown fire in the first two decades of post-fire recovery (Fig. 4). Although this model was weakly significant, it had little explanatory power (R^2 = 0.01).

INSERT FIG. 4 AROUND HERE

Final models

The mean likelihood of fire per annum *L* varied only slightly between formations when all ages were combined (Table 4), however the formations OF and SFW differed notably from the others when age effects were taken into account by finding L_f (Fig. 5a.). This pattern varied again when likelihood of crown fire at a burning site L_{cb} was considered (Fig 5b), and as a result, the combined function L_c produced large differences in the annual likelihood of crown fire at a point (Fig 5c).

INSERT FIG. 5 AROUND HERE

DISCUSSION

Contrary to widely held perceptions of eucalypt forests, feedbacks in the study area have been pronounced and positive in all formations over the past half century. Forest stands have burnt 1.5 (OF) to 8.3 (TWF) times more often in regenerating forest than in mature forest, and crown fires appear to have been mostly confined to regenerating stands.

The degree to which stand age drove flammability varied between formations. The highest R^2 was measured for DOF, where stand age has contributed more than one third of the variability in fire size, regardless of weather and other effects. The lowest R^2 was measured for OF and LDOW, reflecting the influence of a small number of remaining outliers rather than a lack of general trend (Figs. 3b & 3c.), however these were not removed as the model had already been successfully fit at the highest level of significance.

Driving mechanisms

These findings are consistent with broad mechanistic expectations that have been proposed for angiosperm forests (Bond and Midgley 2012), and challenge the expectation of a negative feedback due to fuel accumulation. The "angiosperm revolutions" model of Bond and Midgley (2012) points to the characteristic formation of a gap between ground and canopy fuels in mature forests, which acts to prevent crown fire ignition and leaves an intact canopy to slow wind speeds and resulting fire spread at ground level.

The theory that these aspects of plant structure and spatial relationships drive flammability was compared to standard expectations from fuel load, using the biophysical, mechanistic Forest Flammability Model (FFM, (Zylstra 2011; Zylstra *et al.* 2016)). By validating both approaches against flame heights measured from burn patterns across a large area of the Australian Alps burnt in 2003, the model found that fuel load explained only 11% of the observed variability in flame height, whereas the addition of plant structure and species' composition increased the R^2 to 0.80 (Zylstra *et al.* 2016). When the FFM was used to model SFW flammability dynamics from plant species and structure, the positive feedback measured from FR was reproduced. In contrast, modelling using the fuel load-based approach of McArthur (Noble *et al.* 1980; McArthur 1967) falsely predicted a negative feedback (Zylstra 2013). This model has long been the primary industry-standard approach used for bushfire in eastern Australia (Gould and Cruz 2012).

Fire-induced factors that increased flammability in these studies included the loss of canopy protection for low vegetation, the germination and/or fertilisation of understorey plants, and the loss of a gap between ground and regenerating canopy fuels. Such patterns of regrowth are common in the forests of the Alps, whether due to resprouting or the regrowth of trees from seed (Fig. 6a., b.). Feedback strength is likely to derive from the degree to which these factors change between regenerating and mature forests, so that the strongest feedbacks are evident in forests that change from dense regrowth close to the ground, to mature stands with large separations between dense tree crowns and the lower fuels.

INSERT FIG. 6 AROUND HERE

An implication of this is that less severe fire impacts may produce weaker feedbacks. This may be the case where fires do not kill the crown either through scorch or cambium heating, do not promote growth close to the ground, or do not by some other mechanism such as promotion of epicormic growth remove the gap between ground and canopy fuels. It cannot yet be determined whether such fires can change the direction of feedback by creating a regeneration period that is less flammable than the mature period, but they may produce weaker positive feedbacks. The strength of this effect will depend on the formation in question, as structure and species' sensitivity to fire could have overriding effects (Fig. 6c. to 6f.).

It is notable that the peak in crown fire likelihood occurred later than the FR peak in the three formations that had strong responses (c.f. Figs. 5a and 5b.). This pattern is similar to that modelled for SFW, which predicted a later peak in the effects of flame height than in rate of spread (Zylstra 2011, 2013). If this pattern holds for all communities examined here, it suggests that FR and hence annual burnt area is driven more by spread rate than by difficulty of suppression due to flame height.

In addition to the probable effect of fire severity, the analyses in this study are limited in that they describe historical trends only. If changing atmospheric and climatic influences act to vary species' dominance, structure or leaf traits such as thickness or chemistry, the flammability of component species will also vary, with unforeseen effects on stand flammability. For example, (Prior and Bowman 2014) found that large eucalypt species are likely to grow more slowly in a warmer environment, and as the onset of the mature phase is related to the formation of a sufficient gap between canopy and lower plants, this may act to extend the flammable period of regeneration.

Implications

The findings of this study have significant implications for the Australian Alps, as they demonstrate that positive flammability feedbacks are not only present in the alpine area, but are pronounced and prevalent across the entire forested bioregion. Increases in fire frequency can be expected to result in increased landscape flammability, with greater consequent impacts on resident species, ecosystem processes and human values. As frequency increases, connectivity will increase between areas of flammable landscape, accelerating the effect of exogenous drivers and facilitating fire spread into previous refugia. In some formations, this may push forests toward tipping points leading to ecosystem collapse and alternative stable states.

Such concern has already been raised in regard to the Ash-type forests in the TWF formation (Burns *et al.* 2015; Bowman *et al.* 2014), which are experiencing significant decline due to frequent fire, and to logging in areas adjacent to Park. Two forms of transformation in these forests fit the definition of ecosystem collapse (Keith *et al.* 2013). Firstly, where the canopy is heavily dominated by the obligate-seeding Ash, successive crown deaths within the primary juvenile period result in a distinct tipping point, and consequent transition to shrubland. This transition has been observed in several locations since 2003 (Bowman *et al.* 2014; Wright and Robertson 2014). Secondly, where a resprouting sub-dominant canopy tree such as *E. dalrympleana* is present in sufficient numbers, frequent fire leads to a shift in formation from TWF to OF. This second form of collapse is potentially well advanced already, although differences in survey technique introduce uncertainty in that determination. Early surveys found that *E. delegatensis* almost entirely dominated Ash forest canopies in the NSW Alps (Byles 1932), yet data (G. Wright and G. Robertson, unpublished data, 2014) from recent surveys (Wright and Robertson 2014) showed dominance in only 68% of sites in mapped Ash forest, with other species typical to the OF formation dominating the remaining fraction.

Transition from TWF to OF introduces changes to landscape flammability in the Alps that may be considered permanent on a scale of human management, as mature OF is more flammable than mature TWF (Table 2). In terms of L_f and L_c (Fig. 5a and c) averaged for these mature periods, this represents a doubling in the likelihood of fire at any point, and four times the likelihood that any point will experience crown fire in a given year. This has potential to increase fire contagion and transform the flammability of the entire bioregion.

Concluding remarks

This study constitutes the first examination of fire-flammability feedbacks for these forests, and thereby provides a basis by which fire risk assessment and mitigation can transition from assumed feedbacks to an evidential basis. Across the Australian Alps, recently burnt forests have been on average more flammable than mature forests, consistent with the mechanistic understanding based on plant growth and species' change. Increases in fire frequency are therefore likely to create a more flammable landscape, with implications for both natural and built assets. Drivers of post-fire succession such as fire severity or expected climatic and atmospheric changes may vary the pattern or strength of these feedbacks, but this has yet to be shown through either empirical measurement or mechanistic modelling.

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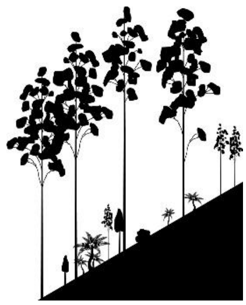
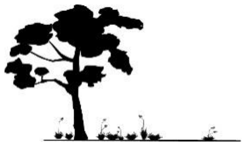
Table 1. Forest formations within the study area, showing details of the component formations[†] in the New South Wales and Australian Capital Territory forests, followed by the Ecological Vegetation Community (EVC) groups[‡] in Victoria.

Mapped area (ha)	Elevation range (m.a.s.l.)	Canopy height (m)	Typical canopy species	Formations EVC Groups	Indicative structure
			Tall Wet Forest (TWF)		
228888	<1400	20-50	*Eucalyptus delegatensis, E. regnans, E. dalrympleana, E. pauciflora, E. fastigata* (Myrtaceae)	Ash eucalypt forests, Rainforests Wet or damp forests, Rainforests	
			Open Forest (OF)		
486891	700-1300	20-35	*Eucalyptus dalrympleana, E. robertsonii subsp. robertsonii, E. macrorhyncha, E. bridgesiana, E. pauciflora, E. viminalis, E. rubida subsp. rubida, E. aggregata, E. stellulata* (Myrtaceae)	Moist eucalypt forests, Montane tableland forests, Swamp forests/sedgelands Montane shrublands, grasslands, or woodlands	
			Subalpine Forest and Woodland (SFW)		
189598	1000-1960	5-15	*Eucalyptus debeuzevillei, Eucalyptus niphophila, Eucalyptus pauciflora* (Myrtaceae)	Subalpine low forests Subalpine shrublands, grasslands or woodlands	
			Dry Open Forest (DOF)		

417005	300-1100	15-20	*E. macrorhyncha, E. rossii, E. dives, E. mannifera* (Myrtaceae)	Grass/shrub forests Dry forests	
			Low, Dry Open Woodland (LDOW)		
94102	< 550	15-30	*Eucalyptus blakelyi, E. melliodora, E. bridgesiana, E. albens, E. polyanthemos subsp. polyanthemos* (Myrtaceae), *Callitris glaucophylla* (Cupressaceae)	Grassy woodlands/grasslands Lower slopes or hills woodlands	
TOTAL 1416586					

†(Gellie 2005), ‡(Department of Sustainability and Environment 2010)

Table 2. Statistics for testing hypotheses and characterising feedbacks for the models that could be fit to the data.

Area burnt (ha)	**Model**	**Model strength**			**Constants**			**Dynamics**, Max age, $\bar{x}$ FR			**Feedback statistics**	
		RSE	**R^2**	[illegible]	**a / sc**	**b / sd**	**$\bar{x}$**	**Y**	**R**	**M**	**YE (years)**	**FS**
Tall Wet Forest (TWF)												
141,255	**Burr**	**10.01**	**0.16**		**2.340*****	**1.602*****		3, *0.98*	21, *1.54*	*0.17*	0	8.3
	Olsen				1.046***	0.575						
Open Forest (OF)												
338,432	Burr	15.59	0.07		2.324***	5.510*						
	Binomial				129.84	35.27	-12.50					
	Olsen				1.033*	0.846						
	Burr_O	**7.39**	**0.01**		**2.221*****	**1.065*****		6, *0.48*	28, *1.29*	*0.73*	4	1.5
Subalpine Forest & Woodland (SFW)												
85,693	**Burr**	**8.50**	**0.09**	**0.63**	**2.230*****	**1.163*****		6, *0.81*	25, *1.31*	*0.50*	3	2.3
	Binomial			0.37	43.319**	11.982*	17.143***					
	Olsen				1.066***	0.382						
Dry Open Forest (DOF)												
331,946	**Burr**	**5.85**	**0.36**	**0.80**	**2.306*****	**1.671*****		3, *0.62*	19, *1.49*	*0.50*	2	2.6
	Binomial			0.2	31.240***	6.496***	11.415***					
	Olsen				1.048***	0.631						
Low, Dry Open Woodland (LDOW)												
	Burr				2.197***	0.521						
	Olsen				1.109**	0.403						
84,254	**Burr_O**	**8.45**	**0.07**		**2.303*****	**2.285*****		2, *0.67*	14, *1.50*	*0.67*	2	2.0

Models that could be fit using NLS are shown, regardless of their goodness of fit. The constants *a* and *b* fit either Burr or Olsen as indicated, and *sc*, *sd* and $\bar{x}$ fit the binomial model, showing significance for each constant (*0.01, **0.001, ***0.0001). Where all constants were significant for more than one model, Akaike Weight is shown for significant models to indicate the likelihood of the best approximating model. Where this was >0.5, the model was further refined for some formations with the removal of outliers, in which case this adjusted model is shown with the suffix _O. Strength of the best model for each formation is given by Residual Standard Error RSE, and R^2.

The Dynamics columns divide the forest into the three age classes young Y (flammability ratio FR < 1), regrowth R (FR ≥ 1), and mature M (second period where FR < 1). The classes Y and R are described by maximum age, and all classes show mean flammability in italics.

Two feedback statistics are given; these are young equivalent YE, which is the number of years after fire for which the FR ≤ the mean FR for M, and feedback strength FS, which is the mean FR for regenerating forests (Y and R) divided by the mean FR for M. In all cases, FS is greater than one, indicating that mean flammability of regrowing forest is greater than the mean flammability of mature forests.

Table 3. Statistics for the models that could be fit to crown fire data.

			Model strength		Constants		
Formation	Model	Samples	RSE	R^2	a / sc	b / s	$\bar{x}$
TWF	Binomial	40	0.057	0.17	1.494^{***}	6.655^{***}	23.704^{***}
OF	Binomial	30	0.078	0.12	4.184^{***}	11.184^{***}	23.206^{***}
DOF	Mean	30	0.167	0.01	1.455^{***}	0.992^{*}	
SFW	Binomial	26	0.132	0.11	4.010^{***}	6.63^{**}	20.356^{***}
LDOW	Mean	20					0.107

Model strength is given by Residual Standard Error RSE and R^2. The constants *sc*, *s* and $\bar{x}$ describe the binomial model (Equation 6), and asterisks indicate their significance (*0.01, **0.001, ***0.0001). Where no model could be fit, the mean of the dataset is given as the Null value.

Table 4. Mean annual likelihood *L* of fire at a point in a formation.

Formation	*L*	Standard error
TWF	0.026	0.013
OF	0.025	0.014
DOF	0.032	0.012
SFW	0.023	0.019
LDOW	0.032	0.016

Figure 1. Location and forest formations composing the study area in south eastern Australia.

Figure 2. Contender functions used to describe flammability dynamics, as per equations 3 - 7

Figure 3. Modelled flammability ratio FR (curved lines), and mean FR values grouped into 5-year clusters. The horizontal broken line shows FR = 1, so that values above the line represent ages that are more flammable than average for that community, and those below the line are less flammable than average. The formations are DOF (a), LDOW with outliers removed (b), OF with outliers removed (c), SFW (d), and TWF (e). Box plots show standard quartile divisions for annual mean data, with outliers up to the default of 1.5 times the interquartile range from the box.

Figure 4. Frequency of crown fire (the highest dNBR class) in decadal groupings of each formation. As per (Hintze and Nelson 1998) violin plots are composed of box plots indicating data range, quartiles, and median, and the shaped area shows the density trace.

Figure 5. Flammability trends for each formation, where the *x*-axis gives years since the last fire, and the *y*-axis gives likelihood for (a) fire burning a point (L_f), (b) crown fire occurring if that point is burning (L_{cb}); and (c) crown fire occurring at any point (L_c).

Fig. 6. Post-fire recovery of (a) DOF with a canopy both resprouting and reseeding, and (b) TWF regenerating from seed alone. Both formations have produced abundant low fuel with little canopy protection. Severity effects vary, depending on the formation. so that in OF, low severity fire can leave the canopy intact, but stimulate ground growth (c), whereas high severity can change both factors (d). In SFW, both low (e) and high (f) severity tend to kill the canopy and promote ground growth, although to differing extents.