High-severity wildfires in temperate Australian forests have increased in extent and aggregation in recent decades

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Abstract

Wildfires have increased in size and frequency in recent decades in many biomes, but have they also become more severe? This question remains under-examined despite fire severity being a critical aspect of fire regimes that indicates fire impacts on ecosystem attributes and associated post-fire recovery. We conducted a retrospective analysis of wildfires larger than 1000 ha in south-eastern Australia to examine the extent and spatial pattern of high-severity burned areas between 1987 and 2017. High-severity maps were generated from Landsat remote sensing imagery. Total and proportional high-severity burned area increased through time. The number of high-severity patches per year remained unchanged but variability in patch size increased, and patches became more aggregated and more irregular in shape. Our results confirm that wildfires in southern Australia have become more severe. This shift in fire regime may have critical consequences for ecosystem dynamics, as fire-adapted temperate forests are more likely to be burned at high severities relative to historical ranges, a trend that seems set to continue under projections of a hotter, drier climate in south-eastern Australia.

Introduction

Wildfire shapes landscape patterns and ecosystem processes as it determines both vegetation distribution and structure [1, 2]. Changes in wildfire activity may alter mortality and regeneration patterns, initiating new successional pathways that ultimately lead to shifts in vegetation composition and landscape attributes [3]. Many studies over the past decades have reported a change in wildfire activity including increases in the frequency, size, and duration of wildfires, as well as the length of the fire season [4–8]. Such increases have been linked to climate change, which influences key fire drivers like fuel accumulation and availability [9–11]. Models based on climate change projections suggest that this trend in increasing fire activity will continue into the future [3, 12–15] posing threats to forest resilience, including shifts to lower density forests or non-forest states [16–18].
Fire severity is a wildfire attribute that quantifies the degree of environmental change caused by fire including immediate fuel consumption and carbon emissions and longer-term impacts on vegetation mortality, successional pathways, and soil substrate [19]. Wildfire severity is spatially heterogeneous and can range from partial litter consumption and light scorching of understorey vegetation to near complete mortality of canopy trees [19–21]. Fire severity and the spatial configuration of severity classes have critical implications for fire-related resilience and potential degradation of ecosystems [21–25]. Wildfire severity is related to fire intensity, which is driven by fuel, climate, and weather [26–29]. As such, fire severity, as for other components of fire regimes, has likely been affected by changing climates in recent decades [30, 31]. In contrast to the large number of studies that have documented recent increases in wildfire area and frequency [9, 32–34], comparatively fewer studies, mostly focused on North America forests, have investigated trends in fire severity, some indicating increases while others indicating no change or decreases [35–37]. Changes in wildfire severity can influence ecological processes by affecting the trajectory of postfire vegetation succession, leading to reductions in forest cover and even conversions to non-forested vegetation [38, 39]. A better understanding of changes in fire severity is crucial to foresee the future pathways of forest systems [40–44].

Australia is one of the most fire-prone countries worldwide [45, 46] with 30.4 million hectares burned across Australia in 2019–2020 alone [47]. Studies have highlighted how climate change has and will continue to impact Australian fire weather and fire activity [31, 48, 49] with fires predicted to become larger and more frequent [50–52]. Whether fires have also become more severe remains largely undocumented. This study’s principal objective was to examine patterns in high-severity fires in temperate forests of the state of Victoria, south-eastern Australia over the last three decades. Specifically, we addressed three questions: 1) Has the area burnt by high-severity fire in temperate forests of Victoria increased in the last 30 years?; 2) Has the spatial configuration of high-severity patches in the landscape changed in the last 30 years; and 3) Are the observed trends consistent across bioclimatic regions?

Materials and methods

Study area and forest types

This study was conducted across the state of Victoria, south-eastern Australia, an area that encompasses 237,659 km², ranges from 0 to 1986 m a.s.l in elevation and comprises several geographical bioregions with differing geology, soils, climate, and predominant vegetation (Table 1 and Fig 1) [53]. Climate across Victoria is temperate with warm to hot summers (average maximum temperature between 16°C and 30°C, [54]). The annual mean temperature ranges from 12.6°C in the south-east region to 14.7°C in the north and north-west regions of the state [55]. The mean annual precipitation varies from 500 to 2,200 mm, with precipitation over 1000 mm in the mountainous areas of the Great Dividing Range [56]. Over the past few decades, Victoria has become warmer and drier, consistent with global trends, and these trends are likely to continue [57–59].

Vegetation affected by the studied wildfires was predominantly comprised of a range of Eucalyptus forests of varying composition, structure and post-fire regeneration strategies [60] (Table 1). These included Mallee, with low canopy height (7 m) and sparse canopy cover (25%), Woodlands with medium canopy height (15 m) and sparse canopy cover, Open forests, with medium to tall canopy height (10–30 m) and mid-dense canopy cover (30–70%) and Closed forests, with tall canopy height (30 m) and dense canopy cover (70–100%) [61]. Obligate seeder tree species are dominant in Closed forest whereas resprouter eucalypts (basal or epicormic) are dominant in all other forest types [60, 62, 63].
We used the wildfire history data available from the Victorian Department of Environment, Land, Water & Planning (‘DELWP’; [64]). Data contained the spatial extent of wildfires since 1926 and, for the most recent fires (from 1998 onward), the start date of the fire. For this study we selected the subset of wildfires that occurred between 1987 and 2017 and that had a minimum burned area of 1000 ha to ensure the fire size was sufficient to include multiple fire-severity levels. That amounted to 211 wildfires that were used to assess changes in the number of fires per year and mean fire size between 1987 and 2017. Each fire was classified according to its dominant bioregion [53]. For the purpose of assessing changes in fire severity, 32 of the 211 wildfires were discarded because pre- or post-fire remote sensing images were unavailable, and 11 were discarded because clouds covered more than 25% of the fire affected area, which may affect the spatial metrics assessed in our study. In total, a subset of 162 wildfires, with at least two fires per year over the past three decades, was used to generate fire-severity maps and analyse changes in severity patterns.

### Remote sensing dataset and spectral indices

Wildfire severity of the selected 162 fires was mapped using Landsat TM, ETM+ and Landsat 8 imagery (30 m spatial resolution, all from Landsat Collection 1, Tier 1). Pre- and post-fire
images were selected for each wildfire based on the recorded fire start dates, which were predominantly in the summer months (December to February). Images were selected within two months before and after the fire to minimise differences in forest phenology and general atmospheric conditions at the time of acquisition. When only the fire year but not start date was recorded (~13% of the fires), we conducted a visual inspection of all images available for the fire season, identified the image where the fire scar was first visible and selected that image and the previous one as post- and pre-fire images respectively for that event. A total of 347 Landsat images including 228 scenes of Landsat 5 (TM), 36 scenes of Landsat 7 (ETM+), and 83 scenes of Landsat 8 (OLI/TIRS) were selected and obtained through the US Geological Survey (USGS) EarthExplorer at http://earthexplorer.usgs.gov as higher level surface reflectance products for each fire. The images were masked for clouds and shadows using the Fmask algorithm [70], which has an accuracy of about 96% [71].

Four spectral indices, namely NBR, NDVI, NDWI, and MSAVI, and their temporal differences (i.e. delta versions, which calculate the change between pre-fire and post-fire spectral index values) were computed for each of the 162 wildfires. These indices are commonly used to assess fire severity [72–76] and were identified by the authors, in a previous study, as the optimal spectral indices for mapping fire severity in the forest types of the study area [77].
Fire severity mapping

Severity of the wildfires in Victoria has not been consistently recorded, with historic fire severity mapping only available for nine years in the period between 1998 and 2014 [78]. To generate fire severity maps for the 162 selected wildfires ensuring the consistency of the classification we used a Random Forest model based on spectral indices that had been previously trained and validated by the authors for the same study area [61]. The reference fire-severity dataset used for training and validation was comprised of 3730 plots from eight large wildfires (>5,000 ha) that occurred between 1998 and 2009 and covered 13 forest types differing in species composition, canopy cover, canopy height and regeneration strategy. These forest types match those affected by the 162 wildfires of this study. Fire severity of the 3730 reference plots had been assessed in situ or visually interpreted on very high resolution orthophotos by the Department of Environment, Water & Planning (DELWP) [78]. Severity was classified as Unburnt: less than 1% of eucalypt and non-eucalypt crowns scorched; Low severity: light scorch of 1–35% of eucalypt and non-eucalypt crowns; Moderate severity: 30–65% of eucalypt and non-eucalypt crowns scorched; or High severity: 70–100% of eucalypt and non-eucalypt crowns burnt [79]. Overall, the reference data included a minimum of 20 plots for each forest type and fire-severity class combination. The Random Forest model was trained with 60% of the data and used 12 predictor variables, which included the four optimal SI indices (dNBR, dNDVI, dNDWI, and dMSAVI) and their pre- and post- fire values. Model accuracy was tested on the remaining 40% of the data that had been left for model validation. Accuracy for high-severity mapping was very high, with a commission error (plots wrongly attributed to high severity) of 0.06 and an omission error (high severity plots incorrectly classified) of 0.18.

Metrics of high-severity fire

Based on the high-severity maps of each of the 162 wildfires, we calculated eight landscape metrics to characterize the extent and spatial configuration of the high-severity burned area. Extent metrics included total and proportional high-severity burned area. Spatial configuration metrics were calculated at the patch level, i.e. areas of high-severity fire surrounded by different severities within the wildfire boundary. Spatial configuration metrics included two patch size metrics (mean patch size, coefficient of variation of patch size), two fragmentation metrics (number of patches, and edge density—a measure of shape complexity) and two aggregation metrics (clumpiness and normalized landscape shape index—NLSI, S1 Table of S1 File). Edge density is the ratio between the total length (m) of the edges of the high-severity patches and the fire size (i.e. total wildfire area burnt at any severity; ha). Low edge density values represent simple shape (e.g. circular) and/or large patches, while large values indicate irregular and/or less continuous patches [80]. Clumpiness and NLSI, both unitless, quantify patch aggregation. The former is based on the likelihood of adjacent pixels belonging to the same class, whereas the later measures the deviation from the hypothetical minimum edge length of the class. Increasing levels of aggregation (i.e. increasing clumsiness and decreasing NLSI) represent more compact and simpler-shaped patches [80, 81]. These metrics describe different aspects of landscape configuration but were not completely independent and therefore should be interpreted jointly (S1 Table of S1 File). Spatial pattern metrics were obtained using the ‘landscapemetric’ package [82] in the R statistical software [83].

Data analysis

Linear regression models were used to evaluate the trends in high-severity fire metrics from 1987 to 2017, with individual fires as the sampling unit. We built two groups of models, a
state-wide model (n = 162 fires) and separate bioregion models. The response variables for both groups of models were the extent or landscape configuration metrics of the high-severity burned area. Predictor variables included year and fire size (i.e. total wildfire area, ha) as fixed effects and bioregion as a random effect, which was only included in the state-wide mixed effects models. Fire size was included as covariate in all models as it can be related to burn patterns [27] and was not correlated with fire year (Pearson’s r = -0.01). Data were transformed when needed to meet assumptions of normality (S1 Table of S1 File). All statistical tests were conducted in the statistical programming language R [83].

Results
Changes in area and proportion of high-severity fire over time
Based on the fire history dataset (n = 211), the number of wildfires per year larger than 1000 ha between 1987 and 2017 increased significantly (P = 0.012), a trend that was mostly due to an increase since 2000 (Fig 2). In contrast, we detected no significant change in total fire size (i.e. all fire severities combined) over that period.

Between 1987 and 2017 the area burnt by high-severity fire increased significantly (P_{Year} < 0.001) even when accounting for total fire size (P_{Fire size} < 0.001; Fig 3 and S1 Fig of S1 File). The same trend was observed for the proportion of the area burnt by high-severity fire (P_{Year} < 0.001; Fig 3). Estimated changes in the area and the proportion of area burnt by high-severity fire over time by bioregions were positive and significant (or marginally significant 0.05 < P < 0.1) in all cases (Fig 3 and S2-S3 Figs of S1 File). The studied bioregions supported quite distinct forest types, from wet, tall, and highly productive to dry, open, and less productive. This suggests that the observed increases in the area burnt by high-severity fire was ubiquitous across regions and did not depend on local environmental conditions or forest types.

![Fig 2. Changes in the number of fires per year and fire size between 1987 and 2017.](https://doi.org/10.1371/journal.pone.0242484.g002)
Changes in spatial patterns of high-severity fire

We detected no changes in fragmentation of wildfires between 1987 and 2017 as evidenced by no significant increases in the number of high-severity patches, a result that was consistent across all bioregions (Figs 4 and 5 and S4 Fig of S1 File). In contrast, edge density, which is related to patch shape complexity, increased over time across Victoria ($P_{\text{Victoria}} = 0.006$), although this trend was only (marginally) significant for the SEC, VM, VVP bioregions ($0.05 < P_{\text{Year}} < 0.1$; Fig 5 and S5).
While mean high-severity patch size did not change significantly, the coefficient of variation of patch size, which was related to fire size, increased in all models ($P_{\text{Year}} < 0.05$ and $P_{\text{Fire size}} < 0.001$; Figs 4 and 5 and S6-S7 Figs of S1 File). Accordingly, we detected an increase in the size of the largest patch ($P_{\text{Year}} = 0.005$; S8 and S9 Figs of S1 File). The level of patch aggregation measured through increased clumpiness and/or decreased Normalized Landscape Shape Index (NLSI), also increased from 1987 to 2017 (Figs 4 and 5 and S10 and S11 Figs of S1 File). This trend, which was significant both at the state and bioregion level, suggests the patterns in high-severity fire changed from a more random, highly-dispersed distribution of patches towards fewer, larger patches of irregular shape that were more aggregated within the fire boundaries.

### Discussion

Our study assessed for the first-time changes in high-fire severity patterns since 1987 in Victoria, south-eastern Australia. We detected an increase in the area burnt at high-severity during that period and a shift in the landscape configuration of high-severity patches, which was consistent across most bioregions, encompassing a broad range of forest types.

**The area of high-severity fire has increased**

Our results showed an increasing trend in both total and proportion of high-severity burned area between 1987 and 2017 across various temperate forests types in south-eastern Australia.
Fig 5. Estimated coefficients for high-severity spatial metrics by bioregions. Each panel displays results for a single model for all regions ("Victoria") and for individual bioregions (Acronyms of bioregions are defined in Table 1); Dot points represent mean estimated coefficient along with the 90th (solid line) and 95th (dashed line) percentile intervals. Coefficients denote significant changes when interval does not include zero. Spatial metrics were log transformed (Number of Patches, Mean Patch Area, Variation Patch Area, NLSI) or arcsine transformed (Edge Density).

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Our findings are in contrast to similar studies conducted in the US where either an increase in fire severity was not detected [37, 84] or the detected increase was due to increasing fire size [36]. Our results also show a covariation between fire size and the extent of the area burned by high-severity fire, a pattern that has been documented before in several north American forests [4, 27, 85–87].

The increasing trends in total and proportion of high-severity burned area at the state level were consistent across all bioregions, indicating that these changes occurred irrespective of forest type and climatic region. This is in contrast to the mixed fire-severity trends assessed across regions in North America [37, 88], which have been argued to be related to fire suppression policies masking climate-change effects [84, 88].

Changes in the area of high-severity fire like those described here have been predicted to occur as a result of climate change since decades ago [89–91]. Our results confirm for the first time that wildfires in south-east Australia are indeed becoming more severe and, given projections of a hotter, drier climate [59], this pattern seems set to continue in coming decades.

Trends in landscape configuration: Aggregation of high-severity patches

Our results showed changes in the landscape configuration of high-severity patches that were consistent at the state level and across bioregions. While we did not detect a significant shift in patch number or mean patch size, we noted an increase in patch size variability, patch shape complexity (measured as edge density) and patch aggregation (as evidenced by trends in clumpiness and NLSI). These changes suggest that the areas burned by high-severity fire have become more aggregated, more irregular in shape, and have a larger area occupied by the largest patch. Similar changes in spatial patterns of high-severity fire have also been reported in fire-severity research in North America [27, 88, 92], where increasing patch aggregation was related to the increased proportion of high-severity area [42].

Implications of increasing high-severity fire for temperate forests in south-east Australia

Our quantified increases in high-severity burned area can lead to concerns about the resilience of Victoria’s temperate forests [20, 93, 94], similar to those expressed for other forest types elsewhere [4, 92, 95]. High-severity fire influences ecosystem dynamics with effects on vegetation succession [25, 96, 97], biogeochemical processes [21, 26, 98], geomorphic processes [99, 100], and habitat availability and biodiversity [23, 101, 102]. Recent high-severity fires within our study area have led to increased mortality of fire-tolerant eucalypt trees and to an increase in the density of young trees vulnerable to subsequent fires [20, 63, 103]. If increasing trends in the extent of high-severity fire detected in our study continue, this indicates potential for large-scale changes in key structural attributes of even the most fire-tolerant forests.

High-severity fire impacts can be modulated by the size, shape, and configuration of high-severity patches. For instance, patch size and aggregation can influence runoff connectivity and post-fire sediment yields and affect the distribution of low- and moderate-severity patches that serve as refuges for fire-sensitive species [104–106]. Patch size and spatial configuration can also affect dispersal and subsequently influence vegetation succession potentially leading to forest-type conversions [107–109]. Delays in tree re-establishment following high-severity fires has been detected in non-serotinous forests of the United States and Canada due to a rapid and extensive shrub establishment via persistent soil seedbanks [109, 110]. Eucalypt forests in south-eastern Australia, including those affected by the studied wildfires, are dominated by either resprouter species that survive most fires, or obligate seeder species that rely on a canopy seedbank to regenerate after fire [63, 111]. Seed dispersal in both resprouters and obligate
seeders eucalypt forests is limited to one or two tree heights, with seeds lacking attributes to facilitate animal or wind dispersal [112]. Resprouters’ seed viability decreases with fire intensity [113] and therefore regeneration in high-severity patches may depend on dispersal from adjacent moderate-severity or unburned patches (although see [20] indicating prolific regeneration from seed of resprouter eucalypts after a single high-severity wildfire). Increases in high-severity patch size though aggregation as observed in this study could hinder post-fire tree establishment by increasing distances from seed source and also altering the regeneration abiotic environment [114] contributing to feedbacks that result in an increased risk of forest-type conversion [115, 116]. Spatial configuration of high-severity patches can also influence regeneration of obligate seeder forests burnt by recurrent fires in quick succession (~20 years; [103]). In such circumstances, trees regenerating after the first fire would not have yet produced meaningful quantities of viable seed before a second fire [117], and eucalypt regeneration would rely on seed dispersal from adjacent patches. Lack of tree regeneration after short-interval fires in obligate seeder forests has been observed in the last decades with aerial sowing being required to address post-fire recovery in obligate seeder forests [118]. This highlights the impact that the observed changes in fire regimes have had on the resilience of eucalypt forests in south-eastern Australia [63, 103].

Conclusions
Changes in high-severity fire, its extent and spatial configuration, can alter a range of ecosystem processes that interactively determine post-fire recovery, including the conversion to non-forest alternative states. Our analysis showed an increase in both the total and proportion of high-severity burned area in Victoria between 1987 and 2017. Over that period, high-severity patches have become more aggregated and more irregular in shape. These trends were consistent across bioregions encompassing a diversity of forest types. Shifts in the spatial patterns of high-severity fire over time may have cascading effects on forest ecology, highlighting the increased threat posed by changing fire regimes to forests ecosystems.

Supporting information
S1 File.
(DOCX)

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References

1. Bond WJ, Keeley JE. Fire as a global ‘herbivore’: the ecology and evolution of flammable ecosystems. Trends in Ecology & Evolution. 2005; 20(7):387–394. https://doi.org/10.1016/j.tree.2005.04.025 PMID: 16701401

2. Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, et al. Fire in the Earth System. Science. 2009; 324(5926):481–484. https://doi.org/10.1126/science.1163886 PMID: 19390038

3. Batllori E, Parisien M-A, Krawchuk MA, Moritz MA. Climate change-induced shifts in fire for Mediterranean ecosystems. Global Ecology and Biogeography. 2013; 22(10):1118–1129. https://doi.org/10.1111/geb.12065

4. Dennison PE, Brewer SC, Arnold JD, Moritz MA. Large wildfire trends in the western United States, 1984–2011. Geophysical Research Letters. 2014; 41(8):2928–2933. https://doi.org/10.1002/2014GL060576

5. Rocca ME, Miniat CF, Mitchel RJ. Introduction to the regional assessments: climate change, wildfire, and forest ecosystem services in the USA. Forest Ecology and Management. 2014; 327:265–268. https://doi.org/10.1016/j.foreco.2014.06.007

6. Westerling AL. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philosophical Transactions of the Royal Society B: Biological Sciences. 2016; 371(1696):20150178. https://doi.org/10.1098/rstb.2015.0178 PMID: 27216510

7. Girardin MP, Mudelsee M. Past and future changes in Canadian boreal wildfire activity. Ecological Applications. 2008; 18(3):391–406. https://doi.org/10.1890/07-0747.1 PMID: 18486604

8. Miller JD, Safford HD, Crimmins M, Thode AE. Quantitative Evidence for Increasing Forest Fire Severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA. Ecosystems. 2009; 12(1):16–32. https://doi.org/10.1007/s10021-008-9209-9

9. Abatzoglou JT, Williams AP. Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of Sciences. 2016; 113(42):11770–11775. https://doi.org/10.1073/pnas.1607171113 PMID: 27791053

10. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. Warming and earlier spring increase western US forest wildfire activity. Science. 2006; 313(5789):940–943. https://doi.org/10.1126/science.1128834 PMID: 16825536

11. Littell JS, McKenzie D, Peterson DL, Westerling AL. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecological Applications. 2009; 19(4):1003–1021. https://doi.org/10.1890/07-1183.1 PMID: 19544740

12. Spracklen DV, Mickley LJ, Logan JA, Hudman RC, Yevich R, Flannigan MD, et al. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. Journal of Geophysical Research: Atmospheres. 2009; 114(D20). https://doi.org/10.1029/2008JD010966

13. Westerling AL, Turner MG, Smithwick EA, Romme WH, Ryan MG. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences. 2011; 108(32):13165–13170. https://doi.org/10.1073/pnas.1110199108 PMID: 21786495

14. Kitzberger T, Falk DA, Westerling AL, Swetnam TW. Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. PLoS One. 2017; 12(12):e0188486. https://doi.org/10.1371/journal.pone.0188486 PMID: 29244839
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15. Stocks BJ, Fosberg M, Lynham T, Mearns L, Wotton B, Yang Q, et al. Climate change and forest fire potential in Russian and Canadian boreal forests. Climatic Change. 1998; 38(1):1–13. https://doi.org/10.1023/A:1005306001055

16. Stevens-Rumann CS, Kemp KB, Higuera PE, Harvey BJ, Rother MT, Donato DC, et al. Evidence for declining forest resilience to wildfires under climate change. Ecology Letter. 2018; 21(2):243–252. https://doi.org/10.1111/ele.12889 PMID: 29230936

17. Aponte C, de Groot WJ, Wotton BM. Forest fires and climate change: causes, consequences and management options. International Journal of Wildland Fire. 2016; 25(8):i–li. https://doi.org/10.1071/WFv25n8 FO

18. Fairman TA, Bennett LT, Tupper S, Nitschke CR. Frequent wildfires erode tree persistence and alter stand structure and initial composition of a fire-tolerant sub-alpine forest. Journal of Vegetation Science. 2017; 28(6):1151–1165. https://doi.org/10.1111/jvs.12575

19. Keeley JE. Fire intensity, fire severity and burn severity: a brief review and suggested usage. International Journal of Wildland Fire. 2009; 18(1):116–126. https://doi.org/10.1071/WF07049

20. Bennett LT, Bruce MJ, MacHunter J, Kohout M, Tanase MA, Aponte C. Mortality and recruitment of fire-tolerant eucalypts as influenced by wildfire severity and recent prescribed fire. Forest Ecology and Management. 2016; 380:107–117. https://doi.org/10.1016/j.foreco.2016.08.047

21. Bennett LT, Bruce MJ, Machunter J, Kohout M, Krishnaraj SJ, Aponte C. Assessing fire impacts on the carbon stability of fire-tolerant forests. Ecological Applications. 2017; 27(8):2497–2513. https://doi.org/10.1002/eap.1626 PMID: 28921765

22. Doer S, Shakesby R, Blake W, Chafer C, Humphreyes G, Wallbrink P. Effects of differing wildfire severities on soil wettability and implications for hydrological response. Journal of Hydrology. 2006; 319(1–4):295–311. https://doi.org/10.1016/j.jhydrol.2005.06.038

23. Chia EK, Bassett M, Nimmo DG, Leonard SW, Ritchie EG, Clarke MF, et al. Fire severity and fire-induced landscape heterogeneity affect arboreal mammals in fire-prone forests. Ecosphere. 2015; 6(10):1–14. https://doi.org/10.1890/ES15-00327.1

24. Wang GG, Kemball KJ. Effects of fire severity on early development of understory vegetation. Canadian Journal of Forest Research. 2005; 35(2):254–262. https://doi.org/10.1139/x04-177

25. Turner MG, Romme WH, Gardner RH, Hargrove WW. Effects of Fire Size and Pattern on Early Succession in Yellowstone National Park. Ecological Monographs. 1997; 67(4):411–433. https://doi.org/10.1890/0012-9615(1997)067[0411:EFSSPS]2.0.CO;2

26. Mitchell SR, Harmon ME, O’Connell KE. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecol Appl. 2009; 19(3):643–55. https://doi.org/10.1890/08-0501.1 PMID: 19425428

27. Cansler CA, McKenzie D. Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. Ecological Applications. 2014; 24(5):1037–1056. https://doi.org/10.1890/13-1077.1 PMID: 25154095

28. Parks SA, Holsinger LM, Panunto MH, Jolly WM, Dobrowski SZ, Dillon GK. High-severity fire: evaluating its key drivers and mapping its probability across western US forests. Environmental Research Letters. 2018; 13(4):044037. https://doi.org/10.1088/1748-9326/aab791

29. Bradstock RA, Hamill KA, Collins L, Price O. Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. Landscape Ecology. 2010; 25(4):607–619. https://doi.org/10.1007/s10980-009-9443-8

30. Parks SA, Miller C, Abatzoglou JT, Holsinger LM, Parisien M-A, Dobrowski SZ. How will climate change affect wildland fire severity in the western US? Environmental Research Letters. 2016; 11(3):035002. https://doi.org/10.1088/1748-9326/11/3/035002

31. Hennessey K, Lucas C, Nicholls N, Bathols J, Suppiah R, Ricketts J. Climate change impacts on fire-weather in south-east Australia. In: CSIRO, editor. Victoria, Australia: CSIRO Marine and Atmospheric Research, Bushfire CRC and Australian Bureau of Meteorology; 2005.

32. Girardin MP. Interannual to decadal changes in area burned in Canada from 1781 to 1982 and the relationship to Northern Hemisphere land temperatures. Global Ecology and Biogeography. 2007; 16(5):557–66. https://doi.org/10.1111/j.1466-8238.2007.00321.x

33. Doer SH, Santin C. Global trends in wildfire and its impacts: perceptions versus realities in a changing world. Philosophical Transactions of the Royal Society B: Biological Sciences. 2016; 371(1696):20150345. https://doi.org/10.1098/rstb.2015.0345 PMID: 27216515

34. Riano D, Moreno Ruiz J, Isidoro D, Ustin S. Global spatial patterns and temporal trends of burned area between 1981 and 2000 using NOAA-NASA Pathfinder. Global Change Biology. 2007; 13(1):40–50. https://doi.org/10.1111/j.1365-2486.2006.01268.x
35. Abatzoglou JT, Kolden CA, Williams AP, Lutz JA, Smith AMS. Climatic influences on interannual variability in regional burn severity across western US forests. International Journal of Wildland Fire. 2017; 26(4). https://doi.org/10.1071/wf16165

36. Keyser AR, Westerling AL. Predicting increasing high severity area burned for three forested regions in the western United States using extreme value theory. Forest Ecology and Management. 2019; 432:694–706. https://doi.org/10.1016/j.foreco.2018.09.027

37. Picotte JJ, Peterson B, Meier G, Howard SM. 1984–2010 trends in fire burn severity and area for the contiguous US. International Journal of Wildland Fire. 2016; 25(4):413–20. https://doi.org/10.1071/wf15039

38. Johnstone JF, Chapin FS, Hollingsworth TN, Mack MC, Romanovsky V, Turetsky M. Fire, climate change, and forest resilience in interior Alaska. Canadian Journal of Forest Research. 2010; 40(7):1302–12. https://doi.org/10.1139/x10-061

39. Parititis J, Veblen TT, Holz A, Gilliam F. Positive fire feedbacks contribute to shifts from Nothofagus pumilio forests to fire-prone shrublands in Patagonia. Journal of Vegetation Science. 2015; 26(1):89–101. https://doi.org/10.1111/jvs.12225

40. Turner MG, Romme WH, Gardner RH. Prefire heterogeneity, fire severity, and early postfire plant reestablishment in subalpine forests of Yellowstone National Park, Wyoming. International Journal of Wildland Fire. 1999; 9(1):21–36. https://doi.org/10.1071/wf99003

41. Baker AG, Catterall C. Where has all the fire gone? Quantifying the spatial and temporal extent of fire exclusion in Byron Shire, Australia. Ecological Management & Restoration. 2015; 16(2):106–13. https://doi.org/10.1111/emr.12161

42. Turner MG, Hargrove WW, Gardner RH, Romme WH. Effects of fire on landscape heterogeneity in Yellowstone national park, Wyoming. Journal of Vegetation Science. 1994; 5(5):731–42. https://doi.org/10.2307/3235886

43. Lentile LB, Holden ZA, Smith AMS, Falkowski MJ, Hudak AT, Morgan P, et al. Remote sensing techniques to assess active fire characteristics and post-fire effects. International Journal of Wildland Fire. 2006; 15(3):319–45. https://doi.org/10.1071/WF05097

44. Keane RE, Cary GJ, Parsons R. Using simulation to map fire regimes: an evaluation of approaches, strategies, and limitations. International Journal of Wildland Fire. 2003; 12(3–4):309–22. https://doi.org/10.1071/WF03017

45. Russell-Smith J, Yates CP, Whitehead PJ, Smith R, Craig R, Allan GE, et al. Bushfires ‘down under’: patterns and implications of contemporary Australian landscape burning. International Journal of Wildland Fire. 2007; 16(4):361–77. https://doi.org/10.1071/WF07018

46. Bradstock RA. A biogeographic model of fire regimes in Australia: current and future implications. Global Ecology and Biogeography. 2010; 19(2):145–58. https://doi.org/10.1111/j.1466-8238.2009.00512.x

47. Boer MM, Resco de Dios V, Bradstock RA. Unprecedented burn area of Australian mega forest fires. Nature Climate Change. 2020; 10(3):171–2. https://doi.org/10.1038/s41558-020-0716-1

48. Pitman A, Narisma G, McAneney J. The impact of climate change on the risk of forest and grassland fires in Australia. Climatic Change. 2007; 84(3–4):383–401. https://doi.org/10.1007/s10584-007-9243-6

49. Clarke H, Lucas C, Smith P. Changes in Australian fire weather between 1973 and 2010. International Journal of Climatology. 2013; 33(4):931–44. https://doi.org/10.1002/joc.3480

50. Bradstock RA, Cohn JS, Gill AM, Bedward M, Lucas C. Prediction of the probability of large fires in the Sydney region of south-eastern Australia using fire weather. International Journal of Wildland Fire. 2009; 18(8):932–43. https://doi.org/10.1071/WF08133.

51. Sharples JJ, Cary GJ, Fox-Hughes P, Mooney S, Evans JP, Fletcher M-S, et al. Natural hazards in Australia: extreme bushfire. Climatic Change. 2016; 139(1):85–99. https://doi.org/10.1007/s10584-016-1811-1

52. Dutta R, Das A, Aryal J. Big data integration shows Australian bush-fire frequency is increasing significantly. Royal Society open science. 2016; 3(2):150241. https://doi.org/10.1098/rsos.150241 PMID: 26998312

53. Environment Australia. Revision of the Interim Biogeographic Regionalisation of Australia (IBRA) and the Development of Version 5.1 Summary Report. Canberra, Australia: Department of Environment and Heritage Canberra, 2000.

54. Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci. 2007; 11(5):1633–1644. https://doi.org/10.5194/hess-11-1633-2007

55. Timbal B, Ekström M, Fiddes S, Grose M, Kirono D, Lim E-P, et al. Climate change science and Victoria—Bureau Research Report No. 014. Bureau of Meteorology; Melbourne Victoria, Australia: Australia. Bureau of Meteorology; 2016.
56. Lacey GC, Grayson RB. Relating baseflow to catchment properties in south-eastern Australia. Journal of Hydrology. 1998; 204(1–4):231–250. https://doi.org/10.1016/s0022-1694(97):00124–8

57. Hughes L, Steffen W. Climate change in Victoria: trends, predictions and impacts. Proceedings of the Royal Society of Victoria. 2013; 125(1):5–13. https://doi.org/10.1071/RS13003

58. Murphy BF, Timbal B. A review of recent climate variability and climate change in southeastern Australia. International Journal of Climatology. 2008; 28(7):859–79. https://doi.org/10.1002/joc.1627

59. Clarke JM, Grose M, Thatcher M, Hermann V, Heady C, Round V, et al. Victorian Climate Projections 2019 Technical Report. Melbourne Australia; 2019.

60. Cheal DC. Growth stages and tolerable fire intervals for Victoria’s native vegetation data sets. Fire and Adaptive Management Report No. 84. East Melbourne, Victoria, Australia: Victorian Government Department of Sustainability and Environment; 2010.

61. Tran BN, Tanase MA, Bennett LT, Aponte C. Fire-severity classification across temperate Australian forests: random forests versus spectral index thresholding. Proceedings of the International Society for Optics and Photonics (SPIE) Remote Sensing 11149, Remote Sensing for Agriculture, Ecosystems, and Hydrology XXI: 2019: International Society for Optics and Photonics. https://doi.org/10.1117/12.2535616

62. Kasel S, Bennett LT, Aponte C, Fredigo M, Nitschke CR. Environmental heterogeneity promotes florigenic turnover in temperate forests of south-eastern Australia more than dispersal limitation and disturbance. Landscape Ecology. 2017; 32(8):1613–29. https://doi.org/10.1007/s10160-017-0526-7

63. Fairman TA, Nitschke CR, Bennett LT. Too much, too soon? A review of the effects of increasing wildfire frequency on tree mortality and regeneration in temperate eucalypt forests. International Journal of Wildland Fire. 2016; 25(8):831–848. https://doi.org/10.1071/WF15010

64. Department of Environment, Land, Water & Planning—DELWP. Fire History Records of Fires Primarily on Public Land. Melbourne, Victoria, Australia: Department of Environment Land Water and Planning; 2017. Available from https://www.data.vic.gov.au/data/dataset/fire-history-records-of-fires-primarily-on-public-land

65. Fick SE, Hijmans RJ. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology. 2017; 37(12):4302–15. https://doi.org/10.1002/joc.5086

66. Cheal D. Growth stages and tolerable fire intervals for Victoria’s native vegetation data sets. Fire and Adaptive Management Report No. 84. East Melbourne, Victoria: Department of Sustainability and Environment; 2010. 1–36 p.

67. Department of Environment, Land, Water & Planning—DELWP. Bioregions and VC benchmarks. 2018. Available from https://www.environment.vic.gov.au/biodiversity/bioregions-and-evc-benchmarks

68. Clarke PJ, Lawes MJ, Murphy BP, Russell-Smith J, Nano CEM, Bradstock R, et al. A synthesis of post-fire recovery traits of woody plants in Australian ecosystems. Science of the Total Environment. 2015; 534:31–42. https://doi.org/10.1016/j.scitotenv.2015.04.002 PMID: 25887372

69. Nicolle D. A classification and census of regeneration strategies in the eucalypts (Angophora, Corymbia and Eucalyptus-Myrtaceae), with special reference to the obligate seeders. Australian Journal of Botany. 2006; 54(4):391–407. https://doi.org/10.1071/BT05061

70. USGS. Earth Explorer 2017 [cited 2017 15 January 2017]. Available from: https://earthexplorer.usgs.gov/.

71. Zhu Z, Woodcock CE. Object-based cloud and cloud shadow detection in Landsat imagery. Remote Sensing of Environment. 2012; 118(Supplement C):83–94. https://doi.org/10.1016/j.rse.2011.10.028

72. Veraverbeke S, Verstraeten WW, Lhermitte S, Goossens R. Evaluating Landsat Thematic Mapper spectral indices for estimating burn severity of the 2007 Peloponnesse wildfires in Greece. International Journal of Wildland Fire. 2010; 19(5):558–69. https://doi.org/10.1071/WF09069

73. Tanase MA, de la Riva J, Pérez-Cabello F. Estimating burn severity at the regional level using optically based indices. Canadian Journal of Forest Research. 2011; 41(4):463–72. https://doi.org/10.1139/x11-011

74. Hoy EE, French NHF, Turetsky MR, Trigg SN, Kasischke ES. Evaluating the potential of Landsat TM/ETM+ imagery for assessing fire severity in Alaskan black spruce forests. International Journal of Wildland Fire. 2008; 17(4):500–14. https://doi.org/10.1071/WF08107

75. Soverel NO, Perrakis DDB, Coops NC. Estimating burn severity from Landsat dNBR and RdNBR indices across western Canada. Remote Sensing of Environment. 2010; 114(9):1896–909. https://doi.org/10.1016/j.rse.2010.03.013

76. Hall RJ, Freeburn JT, de Groot WJ, Pritchard JM, Lynham TJ, Landry R. Remote sensing of burn severity: experience from western Canada boreal fires. International Journal of Wildland Fire. 2008; 17(4):476–89. https://doi.org/10.1071/WF08013
Spatial pattern changes of high-severity wildfires in temperate Australian forests

77. Tran BN, Tanase MA, Bennett LT, Aponte C. Evaluation of Spectral Indices for Assessing Fire Severity in Australian Temperate Forests. Remote Sensing. 2018; 10(11). https://doi.org/10.3390/rs10111680

78. Department of Environment, Land, Water & Planning - DELWP. Aggregated Fire Severity Classes from 1998 onward. Melbourne, Victoria, Australia: Department of Environment Land Water and Planning; 2017. Available from https://discover.data.vic.gov.au/dataset/aggregated-fire-severity-classes-from-1998-onward

79. Haywood A. Remote Sensing Guideline for Assessing Landscape Scale Fire Severity in Victoria’s Forest Estate. Guideline—Reference manual for SOP. 2009;(4).

80. Turner MG, Gardner RH, O’Neill RV, O’Neill RV. Landscape ecology in theory and practice (01st ed.). New York, USA: Springer-Verlag New York: Springer; 2001. https://doi.org/10.1007/b97434

81. McGarigal K, Cushman SA, Ene E. FRAGSTATS v4: Spatial pattern analysis program for categorical and continuous maps. 2012. Available from http://www.umass.edu/landeco/research/fragstats/fragstats.html.

82. Hesselbarth MHK, Sciaini M, With KA, Wiegand K, Nowosad J. Landscapecmetrics: an open-source R tool to calculate landscape metrics. Ecography. 2019; 42:1648–1657. https://doi.org/10.1111/ecog.04617

83. Team RC. R: A language and environment for statistical computing. 2013. Available from https://www.R-project.org/.

84. Hanson CT, Odion DC. Is fire severity increasing in the Sierra Nevada, California, USA? International Journal of Wildland Fire. 2014; 23(1):1–8. https://doi.org/10.1071/WF13016

85. Dillon GK, Holden ZA, Morgan P, Crimmins MA, Heyerdahl EK, Luce CH. Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. Ecosphere. 2011; 2(12):art130. https://doi.org/10.1890/es11-00271.1

86. Miller JD, Knapp EE, Key CH, Skinner CN, Isbell CJ, Creasy RM, et al. Calibration and validation of the relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. Remote Sensing of Environment. 2009; 113(3):645–56. https://doi.org/10.1016/j.rse.2008.11.009

87. Miller JD, Safford H. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and Southern Cascades, California, USA. Fire ecology. 2012; 8(3), 41–57. https://doi.org/10.4996/fireecology.0803041

88. Steel ZL, Koontz MJ, Safford HD. The changing landscape of wildfire: burn pattern trends and implications for California’s yellow pine and mixed conifer forests. Landscape Ecology. 2018; 33(7):1159–76. https://doi.org/10.1007/s10980-018-0665-5

89. Flannigan MD, Wagner CEV. Climate change and wildfire in Canada. Canadian Journal of Forest Research. 1991; 21(1):66–72. https://doi.org/10.1139/x91-010

90. Tom MS, Fried JS. Predicting the impacts of global warming on wildland fire. Climatic Change. 1992; 21(3):257–274. https://doi.org/10.1007/BF00139726

91. Beer T, Gill A, Moore P. Australian bushfire danger under changing climate regimes. In ‘Greenhouse: planning for climate change’. (Ed. Pearman GI) pp. 421–427. CSIRO, Australia. 1988. p. 421–427.

92. Potter C. Fire-climate history and landscape patterns of high burn severity areas on the California southern and central coast. Journal of Coastal Conservation. 2017; 21(3):393–404. https://doi.org/10.1007/s11852-017-0519-3

93. Knox KJE, Clarke PJ. Fire severity, feedback effects and resilience to alternative community states in forest assemblages. Forest Ecology and Management. 2012; 265:47–54. https://doi.org/10.1016/j.foreco.2011.10.025

94. Harmmill K, Penman T, Bradstock R. Responses of resilience traits to gradients of temperature, rainfall and fire frequency in fire-prone, Australian forests: potential consequences of climate change. Plant Ecology. 2016; 217(6):725–41. https://doi.org/10.1007/s11258-016-0578-9

95. Pinno BD, Errington RC, Thompson DK. Young jack pine and high severity fire combine to create potentially expansive areas of understocked forest. Forest Ecology and Management. 2013; 310:517–22. https://doi.org/10.1016/j.foreco.2013.08.055

96. Holz A, Wood SW, Veblen TT, Bowman DM. Effects of high-severity fire drove the population collapse of the subalpine Tasmanian endemic conifer Athrotaxis cupressoides. Glob Chang Biol. 2015; 21(1):445–58. https://doi.org/10.1111/gcb.12674 PMID: 25044347

97. Lentile LB, Morgan P, Hudak AT, Bobbitt MJ, Lewis SA, Smith AM, et al. Post-fire burn severity and vegetation response following eight large wildfires across the western United States. Fire Ecology. 2007; 3(1):91–108.

98. Santin C, Doerr SH, Shakesby RA, Bryant R, Sheridan GJ, Lane PNJ, et al. Carbon loads, forms and sequestration potential within ash deposits produced by wildfire: new insights from the 2009 ‘Black Saturday’ fires, Australia. European Journal of Forest Research. 2012; 131(4):1245–53. https://doi.org/10.1007/s10342-012-0695-8
99. Doerr SH, Cerdá A. Fire effects on soil system functioning: new insights and future challenges. International Journal of Wildland Fire. 2005; 14(4):339–42. https://doi.org/10.1071/wf05094

100. Cawson JG, Sheridan GJ, Smith HG, Lane PNJ. Effects of fire severity and burn patchiness on hillslope-scale surface runoff, erosion and hydrologic connectivity in a prescribed burn. Forest Ecology and Management. 2013; 310:219–33. https://doi.org/10.1016/j.foreco.2013.08.016

101. Lee D, Bond M, Borchert M, Tanner R. Influence of Fire and Salvage Logging on Site Occupancy of Spotted Owls in the San Bernardino and San Jacinto Mountains of Southern California. Journal of Wildlife Management. 2013; 77:1327–1341. https://doi.org/10.1002/jwmg.581

102. Buckingham S, Murphy N, Gibb H. The effects of fire severity on macroinvertebrate detritivores and leaf litter decomposition. PLoS One. 2015; 10(4):e0124556. https://doi.org/10.1371/journal.pone.0124556 PMID: 25880062

103. Bowman DM, Murphy BP, Neyland DL, Williamson GJ, Prior LD. Abrupt fire regime change may cause landscape-wide loss of mature obligate seeders forests. Glob Chang Biol. 2014; 20(3):1008–1015. https://doi.org/10.1111/gcb.12433 PMID: 24132866

104. Boer M, Puigdefàbregas J. Effects of spatially structured vegetation patterns on hillslope erosion in a semiarid Mediterranean environment: a simulation study. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group. 2005; 30(2):149–167. https://doi.org/10.1002/esp.1180

105. Cawson JG, Sheridan GJ, Smith HG, Lane PNJ. Surface runoff and erosion after prescribed burning and the effect of different fire regimes in forests and shrublands: a review. International Journal of Wildland Fire. 2012; 21(7):857–872. https://doi.org/10.1071/wf11160

106. Leonard SW, Bennett AF, Clarke MF. Determinants of the occurrence of unburnt forest patches: potential biotic refuges within a large, intense wildfire in south-eastern Australia. Forest Ecology and Management. 2014; 314:85–93. https://doi.org/10.1016/j.foreco.2013.11.036

107. Harvey BJ, Donato DC, Turner MG. High and dry: Post-fire tree seedling establishment in subalpine forests decreases with post-fire drought and large stand-replacing burn patches. Global Ecology and Biogeography. 2016; 25(6):655–669. https://doi.org/10.1111/geb.12443

108. Collins BM, Roller GB. Early forest dynamics in stand-replacing fire patches in the northern Sierra Nevada, California, USA. Landscape Ecology. 2013; 28(9):1801–1813. https://doi.org/10.1007/s10980-013-9923-8

109. Savage M, Mast J. How resilient are Southwestern ponderosa pine forests after crown fires? Canadian Journal of Forest Research-revue Canadienne De Recherche Forestiere. 2005; 35:967–977. https://doi.org/10.1139/x05-028

110. Knapp EE, Weatherspoon CP, Skinner CN. Shrub seed banks in mixed conifer forests of northern California and the role of fire in regulating abundance. Fire Ecology. 2012; 8(1):32–48. https://doi.org/10.4996/fireecology.0801032

111. Keeley JE, Pausas JG, Rundel PW, Bond WJ, Bradstock RA. Fire as an evolutionary pressure shaping plant traits. Trends in plant science. 2011; 16(8):406–411. https://doi.org/10.1016/j.tplants.2011.04.002 PMID: 21571573

112. Potts BM, Wiltshire RJ, Eucalypt genetics and genecology. In: Williams J, Woinarski J, editors. Eucalypt ecology: individuals to ecosystems. Cambridge, New York: Cambridge University Press; 1997. p. 56–91.

113. Ashton DH. Viability of seeds of Eucalyptus obliqua and Leptospermum juniperinum from capsules subjected to a crown fire. Australian Forestry. 1986; 49(1):28–35. https://doi.org/10.1080/00049158.1986.10674460

114. Muscolo A, Bagnato S, Sidari M, Mercurio R. A review of the roles of forest canopy gaps. Journal of Forest Research. 2014; 25(4):725–736. https://doi.org/10.1007/s11676-014-0521-7

115. Jones CS, Duncan DH, Rumpff L, Thomas FM, Morris WK, Vesk PA. Empirically validating a dense woody regrowth ‘problem’ and thinning ‘solution’ for understory vegetation. Forest Ecology and Management. 2015; 340:153–62. https://doi.org/10.1016/j.foreco.2014.12.006

116. Etchells Etchells H, O’Donnell A, Lachlan McCaw W, Grierson PF. Fire severity impacts on tree mortality and post-fire recruitment in tall eucalypt forests of southwest Australia. Forest Ecology and Management. 2020; 459:117850. https://doi.org/10.1016/j.foreco.2019.117850

117. Flint A. Mountain ash in Victoria’s state forests: Department of Sustainability and Environment. East Melbourne, Victoria; 2007.

118. Bassett OD, Prior LD, Slijkerman CM, Jamieson D, Bowman DM. Aerial sowing stopped the loss of alpine ash (Eucalyptus delegatensis) forests burnt by three short-interval fires in the Alpine National Park, Victoria, Australia. Forest Ecology and Management. 2015; 342:39–48. https://doi.org/10.1016/j.foreco.2015.01.008
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