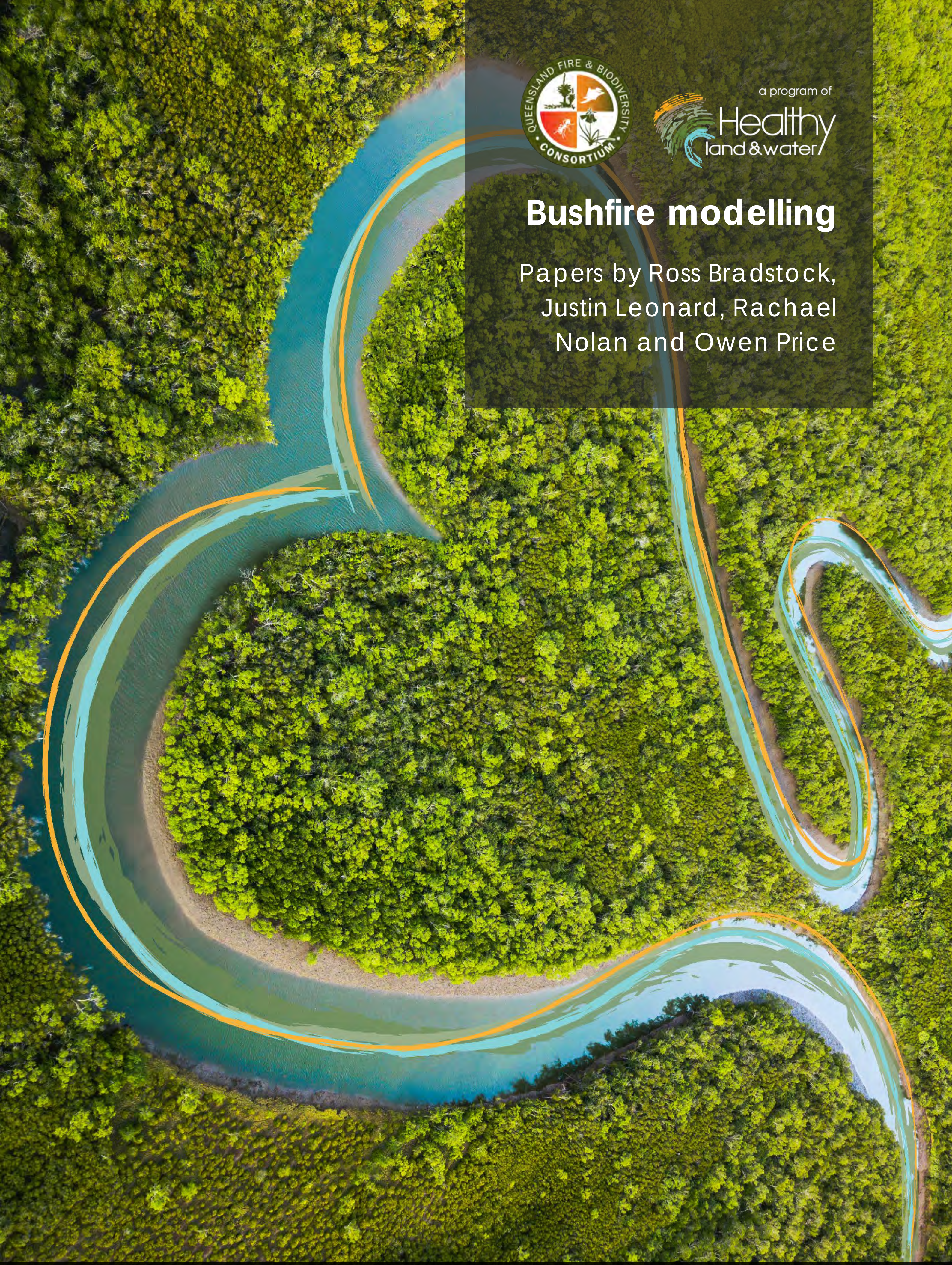
a program of

Bushfire modelling

Papers by Ross Bradstock, Justin Leonard, Rachael Nolan and Owen Price



Delivering an environment for future generations to thrive

Authors

Compiled by Lisa Boyle & Grace Christie, Healthy Land & Water.

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About the Queensland Fire & Biodiversity Consortium

Healthy Land & Water's Queensland Fire & Biodiversity Consortium is a network of land managers and stakeholders devoted to providing a coordinated response and best-practice recommendations for fire management, fire ecology and the conservation of biodiversity in the state of Queensland through education, community engagement and applied research.

About Healthy Land & Water

Healthy Land & Water is the peak environmental group for South East Queensland. For over 20 years it has been dedicated to investing in and leading initiatives to build the prosperity, liveability, and sustainability of our 'future region'. Healthy Land & Water is focused on **delivering an environment for future generations to thrive**.

Our success and strength stems from our extensive knowledge, science and evidence which informs investment in our environment. We are experts in research, monitoring, evaluation and project management. Our team has led many thousands of projects to restore waterways and landscapes, improve native habitats, manage weeds, protect native species, inform policy and educate communities on the best ways to improve and protect the environment.

Working in partnership with Traditional Owners, government, private industry, utilities and the community, Healthy Land & Water delivers innovative and science-based solutions to challenges affecting the environment. Through a combination of scientific expertise and on-ground management works, Healthy Land & Water **leads and connects through science and actions that will preserve and enhance our natural assets and support resilient regions long into the future**.

Acknowledgements

Traditional Owner acknowledgement

We acknowledge that the place we now live in has been nurtured by Australia's First Peoples for tens of thousands of years. We believe the spiritual, cultural and physical consciousness gained through this custodianship is vital to maintaining the future of our region.

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Introduction

This report was produced following discussions at the September 2021 Queensland Fire & Biodiversity Consortium (QFBC) Steering Committee meeting. Members expressed interest in a comprehensive list of scientific bushfire modelling papers published by bushfire researchers Dr Owen Price (Senior Research Fellow at University of Wollongong) and Justin Leonard (Research Leader at CSIRO).

It is intended that this report be used as a reference resource for QFBC partners and for internal use only.

Update: Following discussions at the December QFBC Steering Committee meeting, the report was expanded to include papers by other prominent Australian bushfire modelling researchers. This expanded version includes papers by Dr Rachael Nolan (Hawkesbury Institute for the Environment at Western Sydney University) and Emeritus Professor Ross Bradstock (University of Wollongong).

NB: Please note that the abstracts in this report have been included exactly as they appear in the publishing journal, with no edits.

1 **Balaguer-Romano, R., Diaz-Sierra, R., De Caceres, M., Cunill-Camprubi, A., Nolan, R., Boer, M., Voltas, J., & Resco de Dios, V. (2022). A semi-mechanistic model for predicting daily variations in species-level life fuel moisture content. *Agricultural and Forest Meteorology, 323*. https://doi.org/10.1016/j.agrformet.2022.109022**

Live Fuel Moisture Content (LFMC) is one of the main factors affecting forest ignitability as it determines the availability of existing live fuel to burn. Currently, LFMC is monitored through spectral vegetation indices or inferred from meteorological drought indices. While useful, neither approach provides mechanistic insights into species-specific LFMC variation and they are limited in the ability to forecast LFMC under altered future climates. Here, we developed a semi-mechanistic model to predict daily variation in LFMC across woody species from different functional types by adjusting a soil water balance model which estimates predawn leaf water potential (Ψpd). Our overarching goal was to balance the trade-off between biological realism, which enhances model applicability, and parameterization complexity, which may limit its value within operational settings. After calibration, model predictions were validated against a dataset comprising 1659 LFMC observations across peninsular Spain, belonging to different functional types and from contrasting climates. The overall goodness of fit for our model (R2 = 0.5) was better than that obtained by an existing models based on drought indices (R2 = 0.3) or spectral vegetation indices (R2 = 0.1). We observed the best predictive performance for seeding shrubs (R2 = 0.6) followed by trees (R2 = 0.5) and resprouting shrubs (R2 = 0.4). Through its relatively simple parameterization, the approach developed here may pave the way for a new generation of process-based models that can be used for operational purposes within fire risk mitigation scenarios.

2 **Barker, J., & Price, O. F. (2018). Positive severity feedback between consecutive fires in dry eucalypt forests of southern Australia. *Ecosphere (Washington, D.C)*, *9*(3), e02110–n/a. https://doi.org/10.1002/ecs2.2110**

Fire regimes have long-term effects on ecosystems which can be subtle, requiring study at a large spatial scale and temporal scale to fully appreciate. The way in which multiple fires interact to create a fire regime is poorly understood, and the relationship between the severities of consecutive fires has not been studied in Australia. By overlaying remotely sensed severity maps, our study investigated how the severity of a fire is influenced by previous fire severity. This was done by sampling points at 500-m spacing across 53 fires in dry eucalypt forests of southeast Australia, over a range of time since fire spanning every major fire season for 30 yr. Generalized additive models were used to determine the influence of previous severity on the probability of crown fire and understory fire, controlling for differences in time since fire, topography, and weather. We found that a crown fire is more than twice as likely after a previous crown fire than previous understory fire, and understory fire is more likely after previous understory fire. Our findings are in line with the results of studies from North America and suggest that severe fire promotes further fire. This may be evidence of a runaway positive feedback, which can drive ecological change, and lead to a mosaic of divergent vegetation, but research into more than two consecutive fires is needed to explore this. Our results also suggest that a low-severity prescribed fire may be a useful management option for breaking a cycle of crown fires.

3 **Barker, J., Price, O., & Jenkins, M. (2022). High severity fire promotes a more flammable eucalypt forest structure. *Austral Ecology, 47,* 519-529. https://doi.org/10.1111/aec.13134**

Recent landscape-scale wildfires in eastern Australia have made apparent the need for a greater understanding of the flammability dynamics of forested ecosystems. Fire severity is a measure of the impact of a fire on vegetation, but little is known about the landscape-scale response of the fire-prone dry sclerophyll forests of eastern Australia to different levels of fire severity. Species in these forests have multiple responses to fire, which can be dependent on the fire severity. In this study, we aimed to determine the effect of fire severity on the vegetation structure, and therefore flammability, of these forests. We addressed two hypotheses that 1) High severity fire would result in a denser understory than low severity fire after 5 years and that 2) High severity fire would reduce the vertical separation between understory and canopy after 5 years. Field surveys of 38 forest sites with differing fire severity but standardised time since fire and forest type, in Sydney region of New South Wales, Australia, were used to test these hypotheses. We found lower canopy cover and greater understory cover (0.5–4 m height) after high severity fire compared with sites which burnt at low severity. Vertical separation was less between the canopy and understory at sites after high severity fire than after low severity fire. The greater quantity of understory fuel and greater vertical continuity in fuel structure observed suggests a potential increase in forest flammability after high severity fire compared with lower severity fires in these forest types.

4 Benali, A., Russo, A., Sá, A. C. ., Pinto, R. M. ., Price, O., Koutsias, N., & Pereira, J. M. . (2016). Determining fire dates and locating ignition points with satellite data. *Remote Sensing (Basel, Switzerland)*, *8*(4), 326–. https://doi.org/10.3390/rs8040326

Each wildfire has its own "history", burns under specific conditions and leads to unique environmental impacts. Information on where and when it has started and its duration is important to improve understanding on the dynamics of individual wildfires. This information is typically included in fire databases that are known to have: (i) multiple error sources; (ii) limited spatial coverage and/or time span, and; (iii) often unknown accuracy and uncertainty. Satellite data have a large potential to reduce such limitations. We used active fire data from the MODerate Resolution Imaging Spectroradiometer (MODIS) to estimate fire start/end dates and ignition location(s) for large wildfires that occurred in Alaska, Portugal, Greece, California and southeastern Australia. We assessed the agreement between satellite-derived estimates and data from fire databases, and determined the associated uncertainty. Fire dates and ignition location(s) were estimated for circa 76% of the total burnt area extent for the five study regions. The ability to estimate fire dates and ignitions from satellite data increased with fire size. The agreement between reported and estimated fire dates was very good for start dates (Model efficiency index, MEF = 0.91) and reasonable for end dates (MEF = 0.73). The spatio-temporal agreement between reported and satellite-derived wildfire ignitions showed temporal lags and distances within 12 h and 2 km, respectively. Uncertainties associated with ignition estimates were generally larger than the disagreements with data reported in fire databases. Our results show how satellite data can contribute to improve information regarding dates and ignitions of large wildfires. This contribution can be particularly relevant in regions with scarce fire information, while in well-documented areas it can be used to complement, potentially detect, and correct inconsistencies in existing fire databases. Using data from other existing and/or upcoming satellites should significantly contribute to reduce errors and uncertainties in satellite-derived fire dates and ignitions, as well as improve coverage of small fires.

5 Bendall, E., Bedward, M., Boer, M., Clarke, H., Collins, L., Leigh, A., & Bradstock, R. (2022). Changes in the resilience of resprouting juvenile tree populations in temperate forests due to coupled severe drought and fire. *Plant Ecology, 223,* 907-923. https://doi.org/10.1007/s11258-022-01249-2

Elevated tree mortality and reduced recruitment of new trees linked to drought and fires has been reported across a range of forests over the last few decades. Forests that resprout new foliage epicormically from buds beneath the bark are considered highly resilient to disturbance, but are potentially at risk of elevated mortality, demographic shifts and changes to species composition due to synergistic effects of drought and fire. Despite this, the effects of drought-fire interactions on such forests remain largely unknown. We assessed the effects of drought severity and fire frequency on juvenile mortality, post-fire seedling recruitment and replacement of juvenile trees (balance of recruitment minus mortality) following fire. We compared dry ridgetops and wet gullies (i.e. two forest types that inhabit different topographic positions in the landscape) across a temperate forest in southern Australia. Both forest types experienced higher rates of fire-induced juvenile mortality in areas that had experienced severe drought compared to moderate drought, though mortality rates were generally low across all drought and fire combinations (e.g. (by 16–79 in DSF; 5–11 in WSF). Future increases in the frequency of coupled severe drought and fire could potentially increase the susceptibility of resilient temperate forests to major changes in structure and function.

6 Bendall, E., Bedward, M., Boer, M., Clarke, H., Collins, L., Leigh, A., & Bradstock, R. (2022). Growth enhancements of elevated atmospheric [CO_2] are reduced under drought-like conditions in temperate eucalypts. *Functional Ecology, 36,* 1542-1558. https://doi.org/10.1111/1365-2435.14046

Elevated atmospheric [CO2] (‘eCO2’) may alter species composition within vegetation types by favouring the growth of some species over others. However, other related changes in climate conditions, such as increased frequency and severity of drought, may reduce eCO2 fertilisation effects on plant growth. For many species, it is not known if responses will reflect variability in trait adaptations due to environment. 2. We grew seedlings of nine species of eucalypts indicative of three regional vegetation types (representing a mesic–xeric ecosystem gradient) under two CO2 concentrations (400 parts per million; 640 ppm, i.e. eCO2) and two watering regimes (well-watered; drought-like conditions). 3. Elevated CO2 increased biomass accumulation but drought reduced this effect, with mesic species experiencing larger relative reductions. Elevated CO2 increased the size of storage organs used during resprouting, in the absence of drought. Typical drought responses, such as increased leaf mass per unit area and root mass ratio, were more pronounced in xeric species and were reduced under eCO2. 4. Seedling growth and resprouting may be enhanced by eCO2, suggesting continued dominance of resprouting species in disturbance-prone ecosystems, although severe drought is likely to offset eCO2 fertilisation. Xeric species may cope with drought more effectively under eCO2 than mesic species due to resource acquisition and storage traits that are more responsive.

7 Bendall, E., Bedward, M., Boer, M., Clarke, H., Collins., Leigh, A., Bradstock, R. (2022). Mortality and resprouting responses in forest trees driven more by tree and ecosystem characteristics than drought severity and fire frequency. *Forest Ecology and Management, 509*. https://doi.org/10.1016/j.foreco.2022.120070

Increases in tree mortality linked to drought and fires have been reported across a range of forests globally over the last few decades. Forests that resprout epicormically/aerially should be the most resistant and resilient to changes in fire regime, yet they may be at risk of increased mortality, demographic shifts and changes to species composition due to the compounding effects of drought and fire. Despite this, the synergistic effects of drought and fire frequency on resprouters has received less attention than for obligate seeder tree species. Our study examined the effects of drought severity and fire frequency on the fire resistance of eucalypts (i.e., including Eucalyptus, Angophora and Corymbia) that can resprout epicormically. Following large-scale wildfires and drought in 2013, we conducted field surveys of temperate eucalypt forests in the Sydney Basin Bioregion, focusing on two major Eucalyptus forest assemblages: dry ridgetops and wet gullies. We measured tree size, previous fire damage (i.e., fire scars), bark type, mortality and resprouting position (e.g., canopy, stem, base) of reproductive-age trees. We used a Bayesian modelling approach to derive bounded estimates of response probabilities for trees sampled in each combination of drought severity (mild/moderate versus severe) and fire frequency (low versus high), as well as bounded estimates of differences between trees with and without fire scars, different bark types and drought/fire histories. Eucalypt populations in both vegetation types were resilient to increases in mortality and changes in resprouting position under severe drought and frequent fire, and mortality and resprouting position varied substantially with tree size, fire scar presence/absence and among bark types. Tree mortality and changes in resprouting position were considerably more likely in smaller trees with fire scars. Species with non-compact bark (e.g., fibrous, stringy, rough) were less resilient to lowering in resprouting position, e.g., from canopy to stem. Populations dominated by species that have small stem diameters, thin/noncompact bark and previous fire damage are likely at elevated risk of mortality and changes in resprouting position under future climate change.

8 Berry, L., Driscoll, D. A., Stein, J. A., Blanchard, W., Banks, S. C., Bradstock, R. A., & Lindenmayer, D. B. (2015). Identifying the location of fire refuges in wet forest ecosystems. *Ecological Applications*, *25*(8), 2337–2348. https://doi.org/10.1890/14-1699.1

The increasing frequency of large, high-severity fires threatens the survival of old-growth specialist fauna in fire-prone forests. Within topographically diverse montane forests, areas which experience less severe or fewer fires compared with those prevailing in the landscape may present unique resource opportunities enabling old-growth specialist fauna to survive. Statistical landscape models which identify the extent and distribution of potential fire refuges may assist land managers to incorporate these areas into relevant biodiversity conservation strategies.

We used a case study in an Australian wet montane forest to establish how predictive fire simulation models can be interpreted as management tools to identify potential fire refuges. We examined the relationship between the probability of fire refuge occurrence as predicted by an existing fire refuge model and fire severity experienced during a large wildfire. We also examined the extent to which local fire severity was influenced by fire severity in the surrounding landscape. We used a combination of statistical approaches including generalised linear modelling, variogram analysis and receiver operating characteristics and area under the curve analysis (ROC AUC).

We found that the amount of unburnt habitat and the factors influencing the retention and location of fire refuges varied with fire conditions. Under extreme fire conditions, the distribution of fire refuges was limited to only extremely sheltered, fire-resistant regions of the landscape. During extreme fire conditions, fire severity patterns were largely determined by stochastic factors that could not be predicted by the model. When fire conditions were moderate, physical landscape properties appeared to mediate fire severity distribution.

Our study demonstrates that land managers can employ predictive landscape fire models to identify the broader climatic and spatial domain within which fire refuges are likely to be present. It is essential that within these envelopes, forest is protected from logging, roads and other developments so that the ecological processes related to the establishment and subsequent use of fire refuges are maintained.

9 Borchers-Arriagada, N., Bowman, D. M. J. S., Price, O., Palmer, A. J., Samson, S., Clarke, H., Sepulveda, G., & Johnston, F. H. (2021). Smoke health costs and the calculus for wildfires fuel management: a modelling study. *The Lancet. Planetary Health*, *5*(9), e608–e619. https://doi.org/10.1016/S2542-5196(21)00198-4

Background: Smoke from uncontrolled wildfires and deliberately set prescribed burns has the potential to produce substantial population exposure to fine particulate matter ($PM_{2·5}$). We aimed to estimate historical health costs attributable to smoke-related $PM_{2·5}$ from all landscape fires combined, and the relative contributions from wildfires and prescribed burns, in New South Wales, Australia. Methods: We quantified $PM_{2·5}$ from all landscape fire smoke (LFS) and estimated the attributable health burden and daily health costs between July 1, 2000, and June 30, 2020, for all of New South Wales and by smaller geographical regions. We combined these results with a spatial database of landscape fires to estimate the relative total and per hectare health costs attributable to $PM_{2·5}$ from wildfire smoke (WFS) and prescribed burning smoke (PBS). Findings: We estimated health costs of AU$ 2013 million (95% CI 718–3354; calculated with the 2018 value of the AU$). $1653 million (82·1%) of costs were attributable to WFS and $361 million (17·9%) to PBS. The per hectare health cost was of $105 for all LFS days ($104 for WFS and $477 for PBS). In sensitivity analyses, the per hectare costs associated with PBS was consistently higher than for WFS under a range of different scenarios. Interpretation: WFS and PBS produce substantial health costs. Total health costs are higher for WFS, but per hectare costs are higher for PBS. This should be considered when assessing the trade-offs between prescribed burns and wildfires.

10 Cawson, J., Hemming, V., Ackland, A., Anderson, W., Bowman, D., Bradstock, R., Brown, T. P., Burton, J., Cary, G. J., Duff, T. J., Filkov, A., Furlaud, J. M., Gazzard, T., Kilinc, M., Nyman, P., Peacock, R., Ryan, M., Sharples, J., Sheridan, G., ... Penman, T. D. (2020). Exploring the key drivers of forest flammability in wet eucalypt forests using expert-derived conceptual models. *Landscape Ecology*, *35*(8), 1775–1798. https://doi.org/10.1007/s10980-020-01055-z

Context: Fire behaviour research has largely focused on dry ecosystems that burn frequently, with far less attention on wetter forests. Yet, the impacts of fire in wet forests can be high and therefore understanding the drivers of fire in these systems is vital. Objectives: We sought to identify and rank by importance the factors plausibly driving flammability in wet eucalypt forests, and describe relationships between them. In doing so, we formulated a set of research priorities. Methods: Conceptual models of forest flammability in wet eucalypt forests were elicited from 21 fire experts using a combination of elicitation techniques. Forest flammability was defined using fire occurrence and fireline intensity as measures of ignitability and heat release rate, respectively. Results: There were shared and divergent opinions about the drivers of flammability in wet eucalypt forests. Widely agreed factors were drought, dead fine fuel moisture content, weather and topography. These factors all influence the availability of biomass to burn, albeit their effects and interactions on various dimensions of flammability are poorly understood. Differences between the models related to lesser understood factors (e.g. live and coarse fuel moisture, plant traits, heatwaves) and the links between factors. Conclusions: By documenting alternative conceptual models, we made shared and divergent opinions explicit about flammability in wet forests. We identified four priority research areas: (1) quantifying drought and fuel moisture thresholds for fire occurrence and intensity, (2) modelling microclimate in dense vegetation and rugged terrain, (3) determining the attributes of live vegetation that influence forest flammability, (4) evaluating fire management strategies.

11 Cirulis, B., Clarke, H., Boer, M., Penman, T., Price, O., & Bradstock, R. (2020). Quantification of inter-regional differences in risk mitigation from prescribed burning across multiple management values. *International Journal of Wildland Fire*, *29*(5), 414–426. https://doi.org/10.1071/WF18135

Fire agencies are moving towards planning systems based on risk assessment; however, knowledge of the most effective way to quantify changes in risk to key values by application of prescribed fire is generally lacking. We present a quantification and inter-regional comparison of how risk to management values responds to variations in prescribed burning treatment rate. Fire simulations were run using the PHOENIX RapidFire fire behaviour simulator for two case study landscapes in interface zones in Tasmania and the Australian Capital Territory (ACT), Australia. A Bayesian network approach used these data to explore the influence of treatment and weather on risk from wildfire. Area burnt, length of powerline damaged and length of road damaged responded more strongly to treatment in the ACT than in Tasmania, whereas treatment mitigated house loss and life loss more strongly in Tasmania than the ACT. The effect of prescribed burning treatment rate on area burnt below minimum tolerable fire interval was similar in each case study landscape. Our study shows that the effectiveness of prescribed burning at mitigating area burnt by wildfire and other key values varies considerably across landscapes and values.

12 Clarke, H., Cirulis, B., Penman, T., Price, O., Boer, M., & Bradstock, R. (2022). The 2019-2020 Australian forest fires are a harbinger of decreased prescribed burning effectiveness under rising extreme conditions. *Scientific Reports, 12*. https://doi.org/10.1038/s41598-022-15262-y

There is an imperative for fire agencies to quantify the potential for prescribed burning to mitigate risk to life, property and environmental values while facing changing climates. The 2019–2020 Black Summer fires in eastern Australia raised questions about the effectiveness of prescribed burning in mitigating risk under unprecedented fire conditions. We performed a simulation experiment to test the effects of different rates of prescribed burning treatment on risks posed by wildfire to life, property and infrastructure. In four forested case study landscapes, we found that the risks posed by wildfire were substantially higher under the fire weather conditions of the 2019–2020 season, compared to the full range of long-term historic weather conditions. For area burnt and house loss, the 2019–2020 conditions resulted in more than a doubling of residual risk across the four landscapes, regardless of treatment rate (mean increase of 230%, range 164–360%). Fire managers must prepare for a higher level of residual risk as climate change increases the likelihood of similar or even more dangerous fire seasons.

13 Clarke, H., Gibson, R., Cirulis, B., Bradstock, R. A., & Penman, T. D. (2019). Developing and testing models of the drivers of anthropogenic and lightning-caused wildfire ignitions in south-eastern Australia. *Journal of Environmental Management*, *235*, 34–41. https://doi.org/10.1016/j.jenvman.2019.01.055

Considerable investments are made in managing fire risk to human assets, including a growing use of fire behaviour simulation tools to allocate expenditure. Understanding fire risk requires estimation of the likelihood of ignition, spread of the fire and impact on assets. The ability to estimate and predict risk requires both the development of ignition likelihood models and the evaluation of these models in novel environments. We developed models for natural and anthropogenic ignitions in the south-eastern Australian state of Victoria incorporating variables relating to fire weather, terrain and the built environment. Fire weather conditions had a consistently positive effect on the likelihood of ignition, although they contributed much more to lightning (57%) and power transmission (55%) ignitions than the 7 other modelled causes (8–32%). The built environment played an important role in driving anthropogenic ignitions. Housing density was the most important variable in most models and proximity to roads had a consistently positive effect. In contrast, the best model for lightning ignitions included a positive relationship with primary productivity, as represented by annual rainfall. These patterns are broadly consistent with previous ignition modelling studies. The models developed for Victoria were tested in the neighbouring fire prone states of South Australia and Tasmania. The anthropogenic ignition model performed well in South Australia (AUC = 0.969) and Tasmania (AUC = 0.848), whereas the natural ignition model only performed well in South Australia (AUC = 0.972; Tasmania AUC = 0.612). Model performance may have been impaired by much lower lightning ignition rates in South Australia and Tasmania than in Victoria. This study shows that the spatial likelihood of ignition can be reliably predicted based on readily available meteorological and biophysical data. Furthermore, the strong performance of anthropogenic and natural ignition models in novel environments suggests there are some universal drivers of ignition likelihood across south-eastern Australia.

14 Clarke, H., Nolan, R., Resco De Dios, V, Bradstock, R., Griebel, A., Khanal, S., & Boer, M. (2022). Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand. *Nature Communications, 13,* https://doi.org/10.1038/s41467-022-34966-3

Levels of fire activity and severity that are unprecedented in the instrumental record have recently been observed in forested regions around the world. Using a large sample of daily fire events and hourly climate data, here we show that fire activity in all global forest biomes responds strongly and predictably to exceedance of thresholds in atmospheric water demand, as measured by maximum daily vapour pressure deficit. The climatology of vapour pressure deficit can therefore be reliably used to predict forest fire risk under projected future climates. We find that climate change is projected to lead to widespread increases in risk, with at least 30 additional days above critical thresholds for fire activity in forest biomes on every continent by 2100 under rising emissions scenarios. Escalating forest fire risk threatens catastrophic carbon losses in the Amazon and major population health impacts from wildfire smoke in south Asia and east Africa.

15 Collins, L., Clarke, H., Gausden, S., Nolan, R., Penman, T., & Bradstock, R. (2022). Warmer and drier conditions have increased the potential for large and severe fire seasons across south-eastern Australia. *Global Ecology and Biogeography, 31,* 1933-1948. https://doi.org/10.1111/geb.13514

Aim: The aims were: (1) to identify the environmental drivers of interannual variation in wildfire extent and severity; (2) to examine temporal trends in climatic potential for large and severe wildfires; and (3) to assess whether environmental conditions experienced during the 2019–2020 mega-fire season were anomalous. Location: South-eastern Australia. Time period: 1953–2020. Major taxa studied: Temperate forests. Methods: We used satellite-derived fire severity mapping from 1988 to 2020 to model the effects of drought, weather and fuels on the annual area burned and the proportion of the area burned that was impacted by high-severity fire across four bioregions. Trends in wildfire extent and severity were then estimated from 1953 to 2020 using these derived models and gridded climate data to assess changes in climatic potential for large and severe wildfires. Estimates of wildfire extent and severity for the 2019–2020 fire season were then assessed against prior seasons (1953–2019). Results: Annual area burned was positively related to the severity of seasonal drought and frequency of fire weather conditions that promote substantial daily fire growth. Wildfire severity was elevated in years with severe fire weather and increased with increasing antecedent drought in years without severe fire weather. Fuels had a lesser effect on wildfire extent and severity than climate. Potential fire extent and severity have increased over time in response to an increased severity of drought and worsening fire weather conditions. Estimates of wildfire extent and severity during the 2019–2020 fire season approached the upper extreme within each bioregion, owing to widespread extreme climatic conditions. Main conclusions: The climatic potential for large and severe forest fires has increased across south-eastern Australia since the 1950s, probably because of anthropogenic climate change. The magnitude and severity of the 2019–2020 fires reflected climatic conditions that are driving an increase in the size and severity of wildfires.

16 Collins, L., Day-Smith, M., Gordon, C., & Nolan, R. (2023). Exposure to canopy fire reduces the biomass and stability of carbon stored in fire tolerant eucalypt forests. *Forest Ecology and Management, 528.* https://doi.org/10.1016/j.foreco.2022.120625

Short-interval high severity wildfires threaten the stability of carbon stocks across forest communities, particularly those dominated by ‘fire-sensitive’ trees. However, there is a dearth of research on the effect of these extreme fires on forests dominated by ‘fire-tolerant’ tree species that can resprout from their trunk and branches i.e. epicormic resprouters. We assessed the effect of the severity of two wildfires occurring in short succession (6- year interval) on live and dead above ground carbon stocks (≥2.5 cm diameter) and carbon stability (i.e. the proportion of total carbon stored in live trees) in a temperate eucalypt forest dominated by epicormic resprouters. Four factorial combinations of low severity understorey fire and high severity canopy fire were examined across two wildfires. Carbon stocks were estimated using two approaches, a standard approach that assigns trees to the live and dead pools based on the presence of live foliage, and a novel approach that accounts for partial mortality of branches and stems. When accounting for partial tree mortality, total carbon stocks were greatest following repeated understorey fire and lowest in areas that had recently experienced canopy fire irrespective of canopy fire frequency. Trends in total carbon were driven by substantial reductions in live carbon following canopy fire, which were partially offset by gains in the standing dead carbon pool. Exposure to canopy fire reduced the proportion of carbon stored in live trees, increasing the susceptibility of carbon stocks to future losses through decomposition and consumption by fire. Relative to sites recently exposed to a single canopy fire, exposure to repeated canopy fires did not result in further reductions to carbon stocks or their stability. The standard carbon estimates substantially overestimated live carbon (+59 %) and underestimated dead carbon (-52 %) in areas recently affected by canopy fire, thus underestimating the impact of high severity fires on carbon stability. Our results suggest that carbon stocks in forests dominated by epicormic resprouters are sensitive to losses following canopy fire but are resistant to compounding effects of short-interval high severity fires, owing to the survival of large live stems. Our results highlight the need to account for partial tree mortality and feedbacks between short-interval wildfires when estimating transitions between carbon pools in fire tolerant forests.

17 Collins, L., Trouve, R., Baker, P., Cirulus, B., Nitschke, C., Nolan, R., Smith, L., & Penman, T. (2023). Fuel reduction burning reduces wildfire severity during extreme fire events in south-eastern Australia. *Journal of Environmental Management, 343.* https://doi.org/10.1016/j.envman.2023.118171

Extreme fire events have increased across south-eastern Australia owing to warmer and drier conditions driven by anthropogenic climate change. Fuel reduction burning is widely applied to reduce the occurrence and severity of wildfires; however, targeted assessment of the effectiveness of this practice is limited, especially under extreme climatic conditions. Our study utilises fire severity atlases for fuel reduction burns and wildfires to examine: (i) patterns in the extent of fuel treatment within planned burns (i.e., burn coverage) across different fire management zones, and; (ii) the effect of fuel reduction burning on the severity of wildfires under extreme climatic conditions. We assessed the effect of fuel reduction burning on wildfire severity across temporal and spatial scales (i.e., point and local landscape), while accounting for burn coverage and fire weather. Fuel reduction burn coverage was substantially lower (~20–30%) than desired targets in fuel management zones focused on asset protection, but within the desired range in zones that focus on ecological objectives. At the point scale, wildfire severity was moderated in treated areas for at least 2–3 years after fuel treatment in shrubland and 3–5 years in forests, relative to areas that did not receive fuel reduction treatments (i.e., unburnt patches). Fuel availability strongly limited fire occurrence and severity within the first 18 months of fuel reduction burning, irrespective of fire weather. Fire weather was the dominant driver of high severity canopy defoliating fire by ~3–5 years after fuel treatment. At the local landscape scale (i.e., 250 ha), the extent of high canopy scorch decreased marginally as the extent of recently (<5 years) treated fuels increased, though there was a high level of uncertainty around the effect of recent fuel treatment. Our findings demonstrate that during extreme fire events, very recent (i.e., < 3 years) fuel reduction burning can aid wildfire suppression locally (i.e., near assets) but will have a highly variable effect on the extent and severity of wildfires at larger scales. The patchy coverage of fuel reduction burns in the wildland-urban interface indicates that considerable residual fuel hazard will often be present within the bounds of fuel reduction burns.

18 Desservettaz, P., Naylor, T., Price, O., Samson, S., Kirkwood, J., & Paton-Walsh, C. (2019). Air quality impacts of smoke from hazard reduction burns and domestic wood heating in western Sydney. *Atmosphere*, *10*(9), 557–. https://doi.org/10.3390/atmos10090557

Air quality was measured in Auburn, a western suburb of Sydney, Australia, for approximately eighteen months during 2016 and 2017. A long open-path infrared spectrometer sampled path-averaged concentrations of several gaseous species, while other pollutants such as $PM_{2.5}$ and PM^{10} were sampled by a mobile air quality station. The measurement site was impacted by a number of indoor wood-heating smoke events during cold winter nights as well as some major smoke events from hazard reduction burning in the spring of 2017. In this paper we compare the atmospheric composition during these different smoke pollution events and assess the relative overall impact on air quality from domestic wood-heaters and prescribed forest fires during the campaign. No significant differences in the composition of smoke from these two sources were identified in this study. Despite the hazard reduction burning events causing worse peak pollution levels, we find that the overall exposure to air toxins was greater from domestic wood-heaters due to their higher frequency and total duration. Our results suggest that policy-makers should place a greater focus on reducing wood-smoke pollution in Sydney and on communicating the issue to the public.

19 Dickman, L., Jonko, A., Linn, R., Altintas, I., Atchley, A., Bar, A., Collins, A., Dupuy, J., Gallagher, M., Hiers, J., Hoffman, C., Hood, S., Hurteau, M., Jolly, W., Josephson, A., Loudermilk, E., Ma, W., Michaletz, S., Nolan, R., O'Brien, J., Parsons, R., Partelli-Feltrin, R., Pimont, F., Resco de Dios, V., Restaino, J., Robbins, Z., Sartor, K., Schultz-Fellenz, E., Serbin, S., Sevanto, S., Shuman, J., Sieg, C., Skowronski, N., Weise, D., Wright, M., Xu, C., Yebra, M., & Younes, N. (2022). Integrating plant physiology into simulation of fire behavior and effects. *The New Phytologist, 238(3),* 952-970. https://doi.org/10.1111/nph.18770

Wildfires are a global crisis, but current fire models fail to capture vegetation response to changing climate. With drought and elevated temperature increasing the importance of vegetation dynamics to fire behavior, and the advent of next generation models capable of capturing increasingly complex physical processes, we provide a renewed focus on representation of woody vegetation in fire models. Currently, the most advanced representations of fire behavior and biophysical fire effects are found in distinct classes of fine-scale models and do not capture variation in live fuel (i.e. living plant) properties. We demonstrate that plant water and carbon dynamics, which influence combustion and heat transfer into the plant and often dictate plant survival, provide the mechanistic linkage between fire behavior and effects. Our conceptual framework linking remotely sensed estimates of plant water and carbon to fine-scale models of fire behavior and effects could be a critical first step toward improving the fidelity of the coarse scale models that are now relied upon for global fire forecasting. This process-based approach will be essential to capturing the influence of physiological responses to drought and warming on live fuel conditions, strengthening the science needed to guide fire managers in an uncertain future.

20 Driscoll, D., Bode, M., Bradstock, R. A., Keith, D. A., Penman, T. D., & Price, O. F. (2016). Resolving future fire management conflicts using multicriteria decision making. *Conservation Biology*, *30*(1), 196–205. https://doi.org/10.1111/cobi.12580

Management strategies to reduce the risks to human life and property from wildfire commonly involve burning native vegetation. However, planned burning can conflict with other societal objectives such as human health and biodiversity conservation. These conflicts are likely to intensify as fire regimes change under future climates and as growing human populations encroach farther into fire-prone ecosystems. Decisions about managing fire risks are therefore complex and warrant more sophisticated approaches than are typically used. We applied a multicriteria decision making approach (MCDA) with the potential to improve fire management outcomes to the case of a highly populated, biodiverse, and flammable wildland–urban interface. We considered the effects of 22 planned burning options on 8 objectives: house protection, maximizing water quality, minimizing carbon emissions and impacts on human health, and minimizing declines of 5 distinct species types. The MCDA identified a small number of management options (burning forest adjacent to houses) that performed well for most objectives, but not for one species type (arboreal mammal) or for water quality. Although MCDA made the conflict between objectives explicit, resolution of the problem depended on the weighting assigned to each objective. Additive weighting of criteria traded off the arboreal mammal and water quality objectives for other objectives. Multiplicative weighting identified scenarios that avoided poor outcomes for any objective, which is important for avoiding potentially irreversible biodiversity losses. To distinguish reliably among management options, future work should focus on reducing uncertainty in outcomes across a range of objectives. Considering management actions that have more predictable outcomes than landscape fuel management will be important. We found that, where data were adequate, an MCDA can support decision making in the complex and often conflicted area of fire management.

21 Fisher, R., Lewis, B., Price, O., & Pickford, A. (2022). Barriers to fire spread in norther Australian tropical savannas, deriving fire edge metrics from long term high-frequency fire histories. *Journal of Environmental Management, 301.* https://doi.org/10.1016/j.envman.2021.113864

The savannas of northern Australia are amongst the most fire-prone landscapes in the world. However, over the last fifteen years, increasing effort has been put into reducing fire extent and severity using prescribed burning strategies early in the dry season. This study seeks to improve the application of strategic fire management by providing a more detailed understanding of the landscape features that impede fire spread in Australia's tropical savannas using long-term satellite-derived fire histories. Spatial analysis of fire edges in Kakadu National Park based on fine-scale (30 m) Landsat imagery found that most fires stopped along linear edges, which were primarily associated with known features (roads, rivers and cliffs). Further analysis found linear features with the highest stopping ability covered only 13% of the park but divided the whole park into smaller containment regions. The stopping power of each feature type was found to vary according to their width and to change during the fire season, results that could help plan strategic fuel reduction burns. Similar results were seen with the lower-resolution continental-scale MODIS satellite-derived edge data. The MODIS dataset provided a means for applying fire edge analysis to support planning in areas of northern Australia that lack fine scale fire history mapping.

22 Forehead, H., Barthelemy, J., Arshad, B., Verstaevel, N., Price, O., & Perez, P. (2020). Traffic exhaust to wildfires: PM2.5 measurements with fixed and portable, low-cost LoRaWAN-connected sensors. *PloS One*, *15*(4), e0231778–e0231778. https://doi.org/10.1371/journal.pone.0231778

Air pollution with $PM_{2.5}$ (particulate matter smaller than 2.5 micro-metres in diameter) is a major health hazard in many cities worldwide, but since measuring instruments have traditionally been expensive, monitoring sites are rare and generally show only background concentrations. With the advent of low-cost, wirelessly connected sensors, air quality measurements are increasingly being made in places where many people spend time and pollution is much worse: on streets near traffic. In the interests of enabling members of the public to measure the air that they breathe, we took an open-source approach to designing a device for measuring $PM_{2.5}$. Parts are relatively cheap, but of good quality and can be easily found in electronics or hardware stores, or on-line. Software is open source and the free LoRaWAN-based "The Things Network" the platform. A number of low-cost sensors we tested had problems, but those selected performed well when co-located with reference-quality instruments. A network of the devices was deployed in an urban centre, yielding valuable data for an extended time. Concentrations of $PM_{2.5}$ at street level were often ten times worse than at air quality stations. The devices and network offer the opportunity for measurements in locations that concern the public.

23 Franklin, M., Major, R., Bedward, M., Price, O., & Bradstock, R. (2022). Forest avifauna exhibit enduring responses to historical high-severity wildfires. *Biological Conservation, 269.* https://doi.org/10.1016.j.biocon.2022.109545

Forest fire size, frequency and severity are increasing worldwide, with corresponding reductions in long-unburnt habitat and greater modification of forest structure over wider areas. Understanding the implications for animals is imperative in optimizing management for species persistence and overall biodiversity. We investigated how avian responses to historical high-severity fire differ in forests at short (five years) and mid-range (16 years) time since fire, including whether increased time since fire mitigates any negative responses to high-severity fire. Sites were established in fire-prone dry forests of the Greater Blue Mountains World Heritage Area, Australia. A Bayesian latent variable analysis of bird data obtained from acoustic recordings was used to estimate the occurrence of 74 species in relation to time since fire (short, mid-range), the spatial extent of historical high severity fire (limited, extensive), and their interaction. Time since fire influenced the number of species present, but only where high-severity fire had been extensive. Here, the lowest and highest number of species in the study occurred where time since fire was short and mid-range, respectively. At least ten species responded either positively or negatively to high-severity fire, but for nine of these species the response did not change with time since fire, potentially implicating persistent effects of such fires on habitat. Six other species were unlikely to occur at short time since fire, requiring habitat at mid-range time since fire. This finding suggests that these species would benefit from strategic retention of forest with longer fire-ages under increased fire activity associated with climate change.

24 Franklin, M., Major, R., & Bradstock, R. (2023). Canopy cover mediates the effects of a decadal increase in time since fire on arboreal birds. *Biological Conservation, 277,* https://doi.org/10.1016/j.biocon.2022.109871

Wildfires impact animal populations directly, and indirectly through alteration of forest habitats. Recovery of populations and habitat structure occurs over time since fire, but knowledge is lacking about the relative importance of these processes as drivers of the occurrence of birds in fire-prone forests. We aimed to determine the extent to which canopy cover mediates the effects of a decadal increase in time since fire on the richness and occurrence of canopy bird species. We established sites at either short (5 years) or mid-range (16 years) time since fire in montane dry sclerophyll forests of south-eastern Australia. Canopy cover estimates were derived from airborne LiDAR data. Birds were surveyed using acoustic recorders, with the resulting data analyzed using Bayesian mediation models to partition direct (population processes) and indirect (canopy cover) effects of time since fire on canopy birds. The predictive accuracy of models representing partial mediation (direct and indirect effects) and complete mediation (indirect effects only) were then compared. The direct effects of wildfire on birds were minimal between five and 16 years since fire. Instead, indirect effects prevailed, with species richness and the occurrence of most canopy species increasing as canopy cover regenerated over time since fire. As these forests transition from short to mid-range time since fire, ongoing increases in canopy cover are of primary importance for birds. We recommend an approach to managing avian diversity that incorporates canopy cover in fire planning to optimize the retention of dwindling amounts of older forest under climate change.

25 Gallagher, R., Allen, S., Mackenzie, B., Keith, D., Nolan, R., Rumpff, L., Gosper, C., Pegg, G., Van Leeuwen, S., Ooi, M., Yates, C., Merow, C., Williams, R., Nikolopoulos, E., Beaumont, L., & Auld, T. (2022). An integrated approach to assessing abiotic and biotic threats to post-fire plant species recovery: Lessons from the 2019-2020 Australian fire season. *Global Ecology and Biogeography, 31, 2056-2069*. https://doi.org/10.1111/geb.13478

Aim: Existing abiotic and biotic threats to plant species (e.g., disease, drought, invasive species) affect their capacity to recover post-fire. We use a new, globally applicable framework to assess the vulnerability of 26,062 Australian plant species to a suite of active threats after the 2019–2020 fires. Location: Australia. Time period: 2019–2020. Major species studied: Plants. Methods: Spatial data for existing threats and information on species-level susceptibility were combined with estimates of the extent of range burnt in southern Australia (> 22°S) to assign species against 10 criteria into vulnerability categories (high, medium, low, none, data deficient). We explore in detail results for three threats (drought, disease, feral animals), highlighting where impacts from multiple threats ranked high vulnerability may compound to reduce post-fire recovery. Results: Analysis of the full suite of 10 vulnerability criteria, which encompass a broad range of threats, revealed large numbers of species vulnerable to poor post-fire recovery from one or more different hazards (high vulnerability: 1,243 species; medium vulnerability: 2,450 species). Collectively, 457 plant species that burnt extensively (>

50%) across their range are highly vulnerable to poor recovery due to exposure to pre-fire drought conditions (235 species), disease (186 species), or feral animals (97 species). Of these 457 species, 61 are vulnerable to more than one of these three threats, highlighting how a suite of interacting hazards can impact plant recovery after fire. Main conclusions: While fire can renew plant populations by stimulating recruitment and resetting competitive interactions, the presence of existing threats in post-fire landscapes jeopardizes recovery. The simultaneous impact of multiple threats that impact recovery can create a suite of hazards that contribute to declines and, potentially, extinction. Our method for rapid post-fire vulnerability assessment can be applied to large numbers of plant species or other biota in fire affected regions globally.

26 Gibson, R., White, L., Hislop, S., Nolan, R., & Dorrough, J. (2022). The post-fire stability index; a new approach to monitoring post-fire recovery by satellite imagery. ***Remote Sensing of Environment, 280*****. https://doi.org/10.1016/j.rse.2022.113151**

Ecological resilience is the capacity of a system to maintain function following disturbance. With the frequency and severity of wildfire activity increasing due to warmer and drier global climate conditions, there are increasing reports of declines in ecological resilience and ecosystems at risk of collapse due to post-fire recovery failure. Observational monitoring of post-fire recovery at the landscape scale is important to understand drivers, identify vulnerable ecosystems and prioritize management intervention to support resilience. Defining a suitably representative baseline condition to compare post-fire recovery states against can be challenging, particularly in broad-scale remote sensing approaches. Here, we introduce a new approach to monitoring post-fire recovery by satellite imagery, the post-fire stability index. The method is based on the concept that a disturbed system state will be reflected by increasing or decreasing rates of system change, while undisturbed or recovered system states are characterised by near-zero rates of change. This reflects the typical pattern of diminishing rate of change in post-fire recovery trajectories. We demonstrate strong performance and suitability of the post-fire stability index in comparison to alternative approaches through time series analyses, and independent validation from post-fire vegetation surveys taken at one-year post-fire. The post-fire stability index was consistently the best performing model across all field measures of vegetative response following the fire event. In ecosystems which exhibit postfire resprouting, higher values in the post-fire stability index were associated with higher levels of field-based measures of foliage projective cover and canopy cover (+/− resprouting), and with lower levels of basal and no resprouting. The post-fire stability index provides a relatively simple and practical solution for consistent broad-scale monitoring post-fire recovery with satellite imagery, which together with standardised fire severity mapping, provide extensive opportunities for further fire and landscape ecology research.

27 Griebel, A., Boer, M., Blackman, C., Choat, B., Ellsworth, D., Madden, P., Medlyn, B., Resco de Dios, V., Wujeska-Klause, A., Yebra, M., Younes Cardenas, N., & Nolan. (2022). Specific leaf area and vapour pressure deficit control live fuel moisture content. ***Functional Ecology, 37,*** **719-731. https://doi.org/10.1111/1365-2435**

1. The live fuel moisture content (LFMC) is an important precondition for wildfire activity, yet it remains challenging to predict LFMC due to the dynamic interplay between atmospheric and hydrological conditions that determine the plant's access to, and loss of water. 2. We monitored LFMC and a range of plant water-use traits (predawn and midday leaf water potentials [Ψleaf]), leaf traits (specific leaf area [SLA]), hydrological status (soil water content [SWC] in the shallow layer and full profile) and atmospheric variables (air temperature, vapour pressure deficit [VPD], CO_2 concentrations) in a mature eucalypt woodland at the Eucalyptus Free-Air CO_2 Enrichment (EucFACE) facility during a drought. 3. We combined plant traits, hydrological status and atmospheric variables into a biophysical model to predict LFMC dynamics, and compared these with predictions of LFMC based on a satellite model and established relationships between Ψleaf and LFMC from pressure–volume curves. 4.

Predawn Ψleaf could be well predicted from changes in SWC, but variation in midday Ψleaf and LFMC were more responsive to atmospheric than hydrological variables. The biophysical model explained up to 89% of variability in LFMC and outperformed established approaches to predict LFMC. SLA was the single most important variable to predict LFMC, followed by VPD, which explained 33% of the remaining variability in LFMC. 5. Our study demonstrates that the co-variation of plant traits and atmospheric and hydrological conditions affect LFMC during drought, suggesting a new way forward for predicting LFMC by combining biophysical and satellite-based models of LFMC with seasonal forecasts of meteorological and hydrological variables.

28 Hislop, S., Stone, C., Gibson, R., Roff, A., Choat, B., Nolan, R., Nguyen, T., & Carnegie, A. (2023). Using dense Sentinel-2 time series to explore combined fire and drought impacts in eucalypt forests. *Frontiers in Forest and Global Change.* https://doi.org/10.3389/ffgc.2023.1018936

Following one of the driest years on record, millions of hectares of forests in southeast Australia were burned in the 2019–2020 “Black Summer” wildfires. In addition to the areas burned, drought related canopy collapse, dieback and tree mortality was widely observed. In this paper, we present a method to map canopy damage due to drought and fire across a large area. Sentinel-2 satellite imagery was used in a monthly time series to highlight areas of forest where the Normalized Burn Ratio index was significantly below a pre-disturbance “stable” period. The stable period was defined as the 3 years prior to 2019 and the disturbance thresholds are based on bioregion specific standard deviations below pre-disturbance means. The novel methods enabled drought impacted forests to be identified, including those which were subsequently burned by wildfire. Across the 20 Mha of forests studied, 9.9 Mha (49%) fell below the disturbance threshold. Of that, 5.8 Mha was disturbed by fire and a further 4.1 Mha by drought outside of the fire extent. Within the fire extent, almost 0.9 Mha was identified as being significantly drought affected prior to being burned. An analysis of spectral recovery following substantial rainfall from February 2020 onward indicates that most of the areas impacted by both drought and fire have similar rates of recovery to those impacted only by fire. There are some areas, however, where the combined effects of the “double disturbance” appears to be hindering recovery. The methods presented here are easily transferrable and demonstrate an approach for monitoring forest disturbance at higher temporal and spatial scales than those typically used.

29 Jenkins, M., Bedward, M., Price, O., & Bradstock, R. A. (2020). Modelling bushfire fuel hazard using biophysical parameters. *Forests*, *11*(9), 925–. https://doi.org/10.3390/F11090925

Environmental gradients or biophysical parameters such as climate, topography and geology drive landscape-scale vegetation structure, species distribution and productivity. These gradients have the potential to provide detailed, fine-scale spatial prediction of the accumulation of bushfire fuels and hence fire hazard by elucidating patterns in field information in a consistent and repeatable way. Rapid visual assessment of bushfire fuel hazard via ratings provides fire and land management agencies with a measure of the probability of first attack success and general suppression difficulty of bushfires at a location. This study used generalised additive modelling to examine how measures of fuel hazard, recorded for locations in New South Wales, Australia, varied in response to environmental gradients and whether these gradients could be used to predict fuel hazard at a landscape scale. We found that time since last fire, temperature and precipitation were strong predictors of fuel hazard. Our model predictions for fuel hazard outperformed current operational methods; however, both methods tended to overestimate lower fuel hazard and underestimate higher fuel hazard. Biophysical modelling of fuel hazard provides significant advancement for predicting fuel hazard. These models have the capability to be improved and developed as additional fuel hazard data, fire history mapping and remote sensing of environmental variables advance both spatially and temporally.

30 Jenkins, M., Price, O., Collins, L., Penman, T., & Bradstock, R. (2019). The influence of planting size and configuration on landscape fire risk. *Journal of Environmental Management*, *248*, 109338–109338. https://doi.org/10.1016/j.jenvman.2019.109338

Revegetating cleared land with native trees and shrubs is increasingly used as a means of addressing loss of biodiversity, degraded soil and water resources and sequestration of carbon. However, revegetation also brings a potential to alter fire risk due to changing fuel types across the landscape. Previous research has found that increasing the area of revegetation does not increase the risk of fire at a landscape scale, but it remains unclear whether the design of revegetation can be optimised to minimise risk. We evaluated if size and arrangement of revegetation affects fire size and intensity within an agricultural setting using a simulation modelling approach. Three revegetation planting designs were assessed, including small (3.2 ha) dispersed plantings, small (3.2 ha) plantings clustered into one third of the landscape, and large (29.2 ha) dispersed plantings, all resulting in the same overall percentage of revegetation (approximately 10% of the landscape). We simulated fires using Phoenix Rapidfire under varying planting design, weather, surrounding pasture conditions, and fire suppression. Planting design had little effect on fire sizes across the landscape, with larger plantings resulting in slightly larger fire sizes. Fires were smaller in landscapes with all planting designs compared with current landscape patterns. There was no significant influence of planting design on fire intensity. Weather and suppression had the strongest influence on both fire size and intensity, with larger and more intense fires under extreme weather conditions, with higher adjacent pasture loads and with no simulated suppression. Management of fuel loads in the pasture surrounding revegetation, weather and suppression are far greater risk factors for fire in these landscapes than planting design.

31 Lane, P., Benyon, R., Nolan, R., Keenan, R., & Zhang, L. (2023). Forests, fire and vegetation change impacts on Murray-Darling basin water resources. *Australasian Journal of Water Resources, 27(1),* 68-84. https://doi.org/10.1080/13241583.2023.2179555

The Murray-Darling River system is perhaps Australia's most important, with significant social, cultural and environmental values including 16 Ramsar listed wetlands. The MDB is home to 2.6 million people and produces about $24 billion worth in agricultural production each year (about one-third of total value for Australia). Hydrologic issues, typified by water availability and quality, have existed for many years, peaking during the Millennium drought from 1997 to 2010. Competing interests (i.e. irrigation, tourism, environmental heath), and the declining flows and water quality during droughts, led governments and water management agencies to consider the risks to water resources in the system in the early-mid 2000s. This paper reviews changes to risks associated with forest dynamics, as identified by - afforestation and bushfire – and considers new issues that have emerged since that analysis. It was found that the potential impacts of bushfire on stream flows were over-estimated in past studies, and that a planned significant afforestation expansion into agricultural and grazing land that was projected to reduce stream flows did not occur. While these two risks now do not seem likely to have significant future impacts on flows, or consequent effects on downstream users, the interaction of elevated CO_2 and increasing temperatures on vegetation functioning and subsequent hydrologic consequences at catchment scale require further research and analysis. Reduced rainfall and increased temperatures under future climate change are likely to have an impact on inputs and flows. Uncertainties in how these changes, and feedbacks between climate, drought, more frequent fire and vegetation responses, impact on system hydrology also require further investigation.

32 **Lawes, M., Crisp, M., Clarke, P., Murphy, B., Midgley, J., Russell-Smith, J., Nano, C., Bradstock, R., Enright, N., Fontaine, J., Gosper, C., & Woolley, LA. (2022). Appraising widespread resprouting but variable levels of postfire seeding in Australian ecosystems: the effect of phylogeny, fire regime and productivity. *Australian Journal of Botany, 70(2),* 114-130. https://doi.org/10.1071/BT21110**

Postfire resprouting (R+) and recruitment from seed (S+) are common resilience traits in Australian ecosystems. We classified 2696 woody Australian taxa as R+ or not (R−) and as S+ or not (S−). The proportions of these traits in Australian ecosystems were examined in relation to fire regimes and other ecological correlates, and by trait mapping on a phylogeny scaled to time. Resprouting mapped as an ancestral trait. Postfire reseeding recruitment, while ancient, is more taxonomically restricted and has evolved independently several times. Nevertheless, both R+ and S+ are common in most clades, but negatively correlated at the ecosystem level indicating an evolutionary trade-off related to differences in the severity of fire regimes, determined in part by ecosystem productivity. Thus, R+ was associated with persistence in ecosystems characterised by higher productivity and relatively frequent surface fires of moderate to low severity (fire-productivity hypothesis). S+, the fire-stimulated recruitment by seed, occurred in ecosystems characterised by infrequent but intense crown-fire and top kill, reducing competition between postfire survivors and recruits (fire-resource-competition hypothesis). Consistently large proportions of R+ or S+ imply fire has been a pervasive evolutionary selection pressure resulting in highly fire-adapted and fire resilient flora in most Australian ecosystems.

33 **Le Breton, T., Lyons, M., Nolan, R., Penman, T., Williamson, G., & Ooi, M. (2022). Megafire-induced interval squeeze threatens vegetation at landscape scales. *Frontiers in Ecology and the Environment, 327*. https://doi.org/10.1002/fee.2482**

Wildfires in 2019–2020 broke global records for extent and severity, affirming the arrival of the megafire era. Frequent megafires reflect changes to fire regimes that can negatively impact species and ecosystems. Here, we offer what we believe to be the first comprehensive analysis of megafire impacts on southeastern Australian vegetation communities, combining remote-sensing data, fire-history records, and plant trait-derived fire interval thresholds. In our study area, fires burned over 5.5 million ha. We found that one-third of all native vegetation in this region has burned too frequently following the megafires, particularly impacting fire sensitive vegetation (for example, rainforests). This represents a single-year increase of 36% in the vegetation at risk of interval squeeze (vegetation transitions driven by altered fire regimes) compared to the previous 59 years combined. We demonstrate that megafires can overrun recently burned vegetation and infiltrate refugia, reducing fire intervals beyond the persistence thresholds of plant species and increasing the risk of ecosystem collapse. Averting this will require innovative approaches to fire management. However, if climate change is not addressed, ecosystem collapse may be unavoidable especially for ecosystems adapted to infrequent, high-severity fire.

34 **Linley, G., Jolly, C., Doherty, T., Geary, W., Armenteras, D., Belcher, C., Bliege Bird, R., Duane, A., Fletcher, MS., Giorgis, M., Haslem, A., Jones, G., Kelly, L., Lee, C., Nolan, R., Parr, C., Pausas, J., Price, J., Regos, A., Ritchie, E., Ruffault, J., Williamson, G., Wu, Q., & Nimmo, D. (2022). What do you mean, 'megafire'? *Global Ecology and Biogeography, 31,* 1906-1922. https://doi.org/10.1111/geb.13499**

Background: 'Megafire' is an emerging concept commonly used to describe fires that are extreme in terms of size, behaviour, and/or impacts, but the term's meaning remains ambiguous. Approach: We sought to resolve ambiguity surrounding the meaning of 'megafire' by conducting a structured review of the use and definition of the term in several languages in the peer-reviewed scientific literature. We collated definitions and descriptions of megafire and identified criteria frequently invoked to define megafire. We recorded the size and location of megafires and mapped them to reveal global variation in the size of fires described as megafires. Results: We identified 109 studies that define the term 'megafire' or identify a megafire, with the term first appearing in the peer-reviewed literature in 2005. Seventy one (~65%) of these studies attempted to describe or define the term. There was considerable variability in the criteria used to define megafire, although definitions of megafire based on fire size were most common. Megafire size thresholds varied geographically from > 100–100,000 ha, with fires > 10,000 ha the most common size threshold (41%, 18/44 studies). Definitions of megafire were most common from studies led by authors from North America (52%, 37/71). We recorded 137 instances from 84 studies where fires were reported as megafires, the vast majority (94%, 129/137) of which exceed 10,000 ha in size. Megafires occurred in a range of biomes, but were most frequently described in forested biomes (112/137, 82%), and usually described single ignition fires (59% 81/137). Conclusion: As Earth's climate and ecosystems change, it is important that scientists can communicate trends in the occurrence of larger and more extreme fires with clarity. To overcome ambiguity, we suggest a definition of megafire as fires > 10,000 ha arising from single or multiple related ignition events. We introduce two additional terms – gigafire (> 100,000 ha) and terafire (> 1,000,000 ha) – for fires of an even larger scale than megafires.

35 Losso, A., Challis, A., Gauthey, A., Nolan, R., Hislop, S., Roff, A., Boer, M., Jiang, M., Medlyn, B., & Choat, B. (2022). Canopy dieback and recovery in Australian native forests following extreme drought. *Scientific Reports, 12.* https://doi.org/10.1038/s41598-022-24833-y

In 2019, south-eastern Australia experienced its driest and hottest year on record, resulting in massive canopy dieback events in eucalypt dominated forests. A subsequent period of high precipitation in 2020 provided a rare opportunity to quantify the impacts of extreme drought and consequent recovery. We quantified canopy health and hydraulic impairment (native percent loss of hydraulic conductivity, PLC) of 18 native tree species growing at 15 sites that were heavily impacted by the drought both during and 8–10 months after the drought. Most species exhibited high PLC during drought (PLC:65.1 ± 3.3%), with no clear patterns across sites or species. Heavily impaired trees (PLC> 70%) showed extensive canopy browning. In the post-drought period, most surviving trees exhibited hydraulic recovery (PLC:26.1± 5.1%), although PLC remained high in some trees (50–70%). Regained hydraulic function (PLC< 50%) corresponded to decreased canopy browning indicating improved tree health. Similar drought (37.1 ± 4.2%) and post-drought (35.1 ± 4.4%) percentages of basal area with dead canopy suggested that trees with severely compromised canopies immediately after drought were not able to recover. This dataset provides insights into the impacts of severe natural drought on the health of mature trees, where hydraulic failure is a major contributor in canopy dieback and tree mortality during extreme drought events.

36 Lu, S., Dosseto, A., Lemarchand, D., Dlapa, P., Simkovic, I., & Bradstock, R. (2022). Investigating boron isotopes and FTIR as proxies for bushfire severity. *Catena, 219.* https://doi.org/10.1016/j.catena.2022.106621

Bushfire occurrences will likely be exacerbated by climate change, thus requiring a model to forecast and manage their impacts. However, a robust bushfire model requires new proxies that can infer fire severity responses to past climate variability. A key test to the viability of new fire proxies is whether they record fire severity in the affected soil. We address this by testing Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy and boron (B) isotopes in soil clay fractions from Yengo National Park, southeastern Australia, as proxies for bushfire severity. The isotopic results were also compared to that of clays that reacted with experimentally combusted bark. ATR-FTIR spectroscopy constrains the soil temperature to between 225 and 500 ◦C during high severity fires, based on the lack of dehydroxylation peak characteristics and the increased aromatic to aliphatic organic peak ratios in clays, compared to that of low severity sites. The isotope composition of the non-exchangeable B fraction in clays is lighter after reacting with leaching solutions of bark combusted at higher temperatures. Combustion temperature does not affect the B isotope fractionation during B adsorption onto clays. Changes to the B isotope composition of clays could instead be justified by the varying B concentration and B isotope compositions of the leaching solutions. In Yengo soil clay fractions, sites that experienced a high severity fire show higher δ11B values by about 1.5 ‰, compared to low severity sites- at odds with observations from our experiment using combusted bark. The combustion of leaves from tree crowns in high severity fires could account for the increase in δ11B of clays post-fire. In summary, FTIR spectroscopy of clays could be useful for constraining soil temperature during bushfires, while the B isotope composition of clays appears as a promising proxy for fire severity.

37 Moreira, F., Ascoli, D., Safford, H., Adams, M. A., Moreno, J. M., Pereira, J. M. C., Catry, F. X., Armesto, J., Bond, W., González, M. E., Curt, T., Koutsias, N., McCaw, L., Price, O., Pausas, J. G., Rigolot, E., Stephens, S., Tavsanoglu, C., Vallejo, V. R., ... Fernandes, P. M. (2020). Wildfire management in Mediterranean-type regions: paradigm change needed. *Environmental Research Letters*, *15*(1), 11001–. https://doi.org/10.1088/1748-9326/ab541e

During the last decades, climate and land use changes led to an increased prevalence of megafires in Mediterranean-type climate regions (MCRs). Here, we argue that current wildfire management policies in MCRs are destined to fail. Focused on fire suppression, these policies largely ignore ongoing climate warming and landscape-scale buildup of fuels. The result is a 'firefighting trap' that contributes to ongoing fuel accumulation precluding suppression under extreme fire weather, and resulting in more severe and larger fires. We believe that a 'business as usual' approach to wildfire in MCRs will not solve the fire problem, and recommend that policy and expenditures be rebalanced between suppression and mitigation of the negative impacts of fire. This requires a paradigm shift: policy effectiveness should not be primarily measured as a function of area burned (as it usually is), but rather as a function of avoided socio-ecological damage and loss.

38 Moritz, M., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., Leonard, J., McCaffrey, S., Odion, D. C., Schoennagel, T., & Syphard, A. D. (2014). Learning to coexist with wildfire. *Nature (London)*, *515*(7525), 58–66. https://doi.org/10.1038/nature13946

The impacts of escalating wildfire in many regions — the lives and homes lost, the expense of suppression and the damage to ecosystem services — necessitate a more sustainable coexistence with wildfire. Climate change and continued development on fire-prone landscapes will only compound current problems. Emerging strategies for managing ecosystems and mitigating risks to human communities provide some hope, although greater recognition of their inherent variation and links is crucial. Without a more integrated framework, fire will never operate as a natural ecosystem process, and the impact on society will continue to grow. A more coordinated approach to risk management and land-use planning in these coupled systems is needed.

39 Nolan, R., Anderson, L., Poulter, B., & Varner, J. (2022). Increasing threat of wildfires: the year 2020 in perspective: A Global Ecology and Biogeography special issue. *Global Ecology and Biogeography, 31,* 1898-1905. https://doi.org/10.1111/geb.13588

Aim: Each year, wild and managed fires burn roughly 4 million km2 [~400 million hectares (Mha)] of savanna, forest, grassland and agricultural ecosystems. Land use and climate change have altered fire regimes throughout the world, with a trend toward higher-severity fires found from Australia, the Americas, Europe and Asia, to the Arctic. In 2020, there were notable catastrophic fires in Australia (in the 2019/20 Austral fire season), the Western United States, South America and Siberia. These fires defined much of the global fire year and were compounded by the socio-economic disruption of the Coronavirus 2019 (COVID-19) pandemic. Location: Global. Time period: 2020. Major taxa studied: Flora and fauna. Methods: The Global Ecology and Biogeography special issue, 'Increasing threat of wildfires: the year 2020 in perspective', includes 18 papers that catalogue these fire events, their drivers and their impacts on flora and fauna. Results: Collectively, these papers highlight the importance of fire response traits, exposure and sensitivity to interacting threats in determining fire impacts. Main conclusions: The scale of the 2020 megafires has helped identify new research areas required to more comprehensively assess fire impacts on biodiversity and biogeochemistry and to inform ecosystem management.

40 Nolan, R., Blackman, C. J., de Dios, V. R., Choat, B., Medlyn, B. E., Li, X., Bradstock, R. A., & Boer, M. M. (2020). Linking forest flammability and plant vulnerability to drought. *Forests*, *11*(7), 779–. https://doi.org/10.3390/F11070779

Globally, fire regimes are being altered by changing climatic conditions. New fire regimes have the potential to drive species extinctions and cause ecosystem state changes, with a range of consequences for ecosystem services. Despite the co-occurrence of forest fires with drought, current approaches to modelling flammability largely overlook the large body of research into plant vulnerability to drought. Here, we outline the mechanisms through which plant responses to drought may affect forest flammability, specifically fuel moisture and the ratio of dead to live fuels. We present a framework for modelling live fuel moisture content (moisture content of foliage and twigs) from soil water content and plant traits, including rooting patterns and leaf traits such as the turgor loss point, osmotic potential, elasticity and leaf mass per area. We also present evidence that physiological drought stress may contribute to previously observed fuel moisture thresholds in south-eastern Australia. Of particular relevance is leaf cavitation and subsequent shedding, which transforms live fuels into dead fuels, which are drier, and thus easier to ignite. We suggest that capitalising on drought research to inform wildfire research presents a major opportunity to develop new insights into wildfires, and new predictive models of seasonal fuel dynamics.

41 Nolan, R., Boer, M. M., Resco de Dios, V., Caccamo, G., & Bradstock, R. A. (2016). Large-scale, dynamic transformations in fuel moisture drive wildfire activity across southeastern Australia. Geophysical Research Letters, 43(9), 4229–4238. https://doi.org/10.1002/2016GL068614

The occurrence of large, high-intensity wildfires requires plant biomass, or fuel, that is sufficiently dry to burn. This poses the question, what is “sufficiently dry”? Until recently, the ability to address this question has been constrained by the spatiotemporal scale of available methods to monitor the moisture contents of both dead and live fuels. Here we take advantage of recent developments in macroscale monitoring of fuel moisture through a combination of remote sensing and climatic modelling. We show there are clear thresholds of fuel moisture content associated with the occurrence of wildfires in forests and woodlands. Furthermore, we show that transformations in fuel moisture conditions across these thresholds can occur rapidly, within a month. Both the approach presented here, and our findings, can be immediately applied and may greatly improve fire risk assessments in forests and woodlands globally.

42 Nolan, R., Collins, L., Gibson, R., Samson, S., Rolls, K., Milner, K., Medlyn, B., Price, O., Griebel, A., Choat, B., Jiang, M., & Boer, M. (2022). The carbon cost of the 2019-20 Australian fires varies with fire severity and forest type. *Global Ecology and Biogeography, 31,* 2131-2146. https://doi.org/10.1111/geb.13548

Aim: To estimate loss of above-ground carbon (AGC) and conversion of live carbon to dead carbon following understorey and canopy fire. Location: South-eastern Australia. Time period: 2019–2020. Major taxa studied: Four widespread resprouting eucalypt forests. Methods: Above-ground carbon was measured in 15 plots in each of four forest types one-year post-fire. We also assessed topkill, that is, trees subject to canopy loss that failed to resprout epicormically. Results: While canopy fire was associated with greater declines in AGC than understorey fire, this was only statistically significant for only one forest type, where AGC declined from 154 to 85 Mg C ha−1 following canopy fire. Significant post-fire increases in dead AGC were observed in one forest type, where dead carbon increased from 22 to 60% after canopy fire. Topkill of trees following canopy fire (48–78% of stems) was higher than topkill after understorey fire (36–53% of stems) and in unburnt forest (12–55%). Topkill occurred primarily in small-diameter stems. Consequently, there was no effect of fire on the proportion of dead AGC in trees, with the exception of the forest with lowest productivity (i.e., lowest biomass) and lowest annual rainfall, where dead tree carbon increased from 8% in unburnt forest to 13 and 53% after understorey and canopy fire, respectively. AGC in understorey vegetation and coarse woody debris was similar or lower in burnt compared with unburnt forest. Litter carbon was significantly lower and pyrogenic carbon significantly higher in burnt forest, with no difference between understorey and canopy fire. Main conclusions: While increased fire severity was associated with increased changes to carbon stocks, there were differences among forest types. Specifically, the driest forest type had the highest rates of topkill following canopy fire. These results highlight the importance of spatial variability in fire severity and forest type in determining the effects of fire on carbon stocks.

43 Nolan, R., Foster, B., Griebel, A., Choat, B., Medlyn, B., Yebra, M., Younes, N., & Boer, M. (2022). Drought-related leaf functional traits control spatial and temporal dynamics of live fuel moisture content. *Agricultural and Forest Meteorology, 319*. https://doi.org/10.1016/j.agrformet.2022.108941

Large forest fires generally occur when the moisture content of fuels is low. For live fuels, our understanding of the physiological basis of variation in moisture content has recently advanced. However, process-based models of live fuel moisture content (LFMC) remain elusive. Here, we aim to further our understanding of the role of physiological mechanisms and plant functional traits in driving spatiotemporal variations in LFMC. We examined whether temporal variation in LFMC could be predicted from pressure-volume curve data, which measures leaf water potential and water content on cut shoots dehydrating on a bench. We also examined whether leaf dry mass traits could predict spatial variation in maximum LFMC. We undertook our study in eucalypt forests and woodlands spanning a large climatic gradient in eastern Australia. We found that LFMC models developed from pressure-volume curves reliably predicted seasonal variation in LFMC across four co-occurring species. A two phase LFMC model, which fit models above and below the turgor loss point (mean absolute error = 3.7- 33.2%), performed similarly well to a simple linear model (mean absolute error = 3.4-35.3%). Across a large climatic gradient, the maximum LFMC of 16 species was correlated with specific leaf area (R2 = 0.54), with the exception of one species with terete terminal stems. Maximum LFMC was highly correlated with aridity (R2 = 0.82), with lower LFMC observed in more arid sites. Our study demonstrates that spatiotemporal dynamics of LFMC are governed by both leaf dry mass traits and the relationship between leaf water potential and water content, which in turn is determined by traits such as cell wall elasticity. Thus, incorporating these traits into models of LFMC, whether these models are based on drought indices, soil moisture, or remotely sensed imagery, is likely to improve overall model performance, and subsequently improve forecasts of wildfire danger.

44 Nolan, R., Price, O. F., Samson, S. A., Jenkins, M. E., Rahmani, S., & Boer, M. M. (2022). Framework for assessing live fine fuel loads and biomass consumption during fire. *Forest Ecology and Management*, *504*, 119830–. https://doi.org/10.1016/j.foreco.2021.119830

Accurate quantification of fine fuel loads (e.g. foliage and twigs) in forests is required for many fire behaviour models, and for assessing post-fire changes in carbon stocks and modelling smoke emissions. Fine fuels burn readily and are thus often targeted for fuel load assessments. Estimates of fine live fuel loads often rely on visual assessments or utilise allometric equations that relate stem diameter of plants to total above-ground biomass. Here, we develop allometric equations for shrubs that relate stem diameter to the portion of above-ground biomass comprised of fine fuel. Our study area is within the temperate eucalypt forests of south-eastern Australia. We present equations for (i) foliage; (ii) all biomass < 3 mm diameter; (iii) all biomass < 6 mm diameter; and (iv) all above-ground biomass. Simple power-law models were developed for five shrub species and saplings of two tree species. Models combining all species (RMSE = 0.03–0.0.06) worked similarly well to species-specific models (RMSE = 0.01–0.08). We then applied these all-species combined models to field observations of shrub stem diameters, measured before and after planned burns. In unburnt forest, the proportion of shrub biomass comprised of fine fuel varied considerably (from 6 to 58%). Fine fuel loads were positively related to total above-ground biomass ($R^2 = 0.75$) and basal area of shrubs ($R^2 = 0.79$). There was considerable variation in consumption of fine fuel. The median reduction in fine fuel load was 22.4%, whereas the median reduction in total above-ground biomass was only 2.3%. Our models of shrub fine fuels can be readily applied to field-based assessments or combined with existing models or remotely sensed estimates of above-ground biomass to model fine fuel loads over large heterogeneous study areas.

45 Nolan, R., Rahmani, S., Samson, S. A., Simpson-Southward, H. M., Boer, M. M., & Bradstock, R. A. (2020). Bark attributes determine variation in fire resistance in resprouting tree species. Forest Ecology and Management, 474, 118385–. https://doi.org/10.1016/j.foreco.2020.118385

Predicting the impact of wildfires on ecosystem services and habitat values requires quantifying rates of post-fire tree mortality and topkill. For those species that resprout epicormically (i.e. from above-ground buds), rates of post-fire topkill (death of aboveground biomass) can vary considerably. Laboratory studies indicate that bark attributes are key determinants of post-fire topkill in these resprouting species. Specifically, bark thickness and bark density influence the capacity of bark to insulate the cambium from the lethal temperatures generated during wildfires. Field studies are generally consistent with these laboratory studies and demonstrate that smaller trees, with thinner bark, are more vulnerable to post-fire topkill. However, comparatively few studies model topkill explicitly as a function of bark thickness, and fewer still model topkill as a function of bark density. In this study we measured post-fire mortality and topkill across eight tree species with varying bark types. We also estimated pre-fire bark thickness (from relationships between stem diameter and bark thickness derived from unburnt forest) and measured bark density. We undertook our study at two dry sclerophyll eucalypt forests located in eastern Australia. The two study areas were subject to wildfire 18 months prior to measurements, with one site characterised by a semi-arid climate, and the second site (located 400 km south-east) characterised by a humid climate. We found that species with thick bark and a low bark density were most resistant to topkill. We defined vulnerability to topkill as the stem diameter associated with a 50% probability of topkill, estimated from logistic regressions. Multiple linear regression indicated that bark thickness and density accounted for 65% of the variation in vulnerability to topkill among species. This regression excluded one species; *Eucalyptus crebra*, which was identified as an outlier. This species was the most vulnerable to topkill and was located at the semi-arid study site. This study site had been subject to a more severe pre-fire drought than the mesic site, suggesting that drought may also have influenced post-fire topkill. However, it is not possible to exclude other species-specific factors or site factors such as climate or fire intensity, which may also have impacted the probability of topkill. Our results demonstrate that bark thickness and density are critically important in developing predictive models of post-fire topkill in resprouting forests.

46 Nolan, R., Resco de Dios, V., Boer, M. M., Caccamo, G., Goulden, M. L., & Bradstock, R. A. (2016). Predicting dead fine fuel moisture at regional scales using vapour pressure deficit from MODIS and gridded weather data. *Remote Sensing of Environment*, *174*(C), 100–108. https://doi.org/10.1016/j.rse.2015.12.010

Spatially explicit predictions of fuel moisture content are crucial for quantifying fire danger indices and as inputs to fire behaviour models. Remotely sensed predictions of fuel moisture have typically focused on live fuels; but regional estimates of dead fuel moisture have been less common. Here we develop and test the spatial application of a recently developed dead fuel moisture model, which is based on the exponential decline of fine fuel moisture with increasing vapour pressure deficit (D). We first compare the performance of two existing approaches to predict D from satellite observations. We then use remotely sensed D, as well as D estimated from gridded daily weather observations, to predict dead fuel moisture. We calibrate and test the model at a woodland site in South East

Australia, and then test the model at a range of sites in South East Australia and Southern California that vary in vegetation type, mean annual precipitation (129–1404 mm year^{-1}) and leaf area index (0.1–5.7). We found that *D* modelled from remotely sensed land surface temperature performed slightly better than a model which also included total precipitable water (MAE < 1.16 kPa and 1.62 kPa respectively). *D* calculated with observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite was under-predicted in areas with low leaf area index. Both *D* from remotely sensed data and gridded weather station data were good predictors of the moisture content of dead suspended fuels at validation sites, with mean absolute errors less than 3.9% and 6.0% respectively. The occurrence of data gaps in remotely sensed time series presents an obstacle to this approach, and assimilated or extrapolated meteorological observations may offer better continuity.

47 Price, O., & Baker, B. (2007). Fire regimes and their correlates in the Darwin region of northern Australia. *Pacific Conservation Biology*, *13*(3), 177–188. https://doi.org/10.1071/PC070177

A nine year fire history for the Darwin region was created from Landsat imagery, and examined to describe the fire regime across the region. 43% of the region burned each year, and approximately one quarter of the fires occur in the late dry season, which is lower than most other studied areas. Freehold land, which covers 35% of the greater Darwin region, has 20% long-unburnt land. In contrast, most publicly owned and Aboriginal owned land has very high fire frequency (60-70% per year), and only 5% long unburnt. It seems that much of the Freehold land is managed for fire suppression, while the common land is burnt either to protect the Freehold or by pyromaniacs. Generalized Linear Modelling among a random sample of points revealed that fire frequency is higher among large blocks of savannah vegetation, and at greater distances from mangrove vegetation and roads. This suggests that various kinds of fire break can be used to manage fire in the region. The overall fire frequency in the Darwin region is probably too high and is having a negative impact on wildlife. However, the relatively low proportion of late dry season fires means the regime is probably not as bad as in some other regions. The management of fire is ad-hoc and strongly influenced by tenure. There needs to be a clear statement of regional fire targets and a strategy to achieve these. Continuation of the fire mapping is an essential component of achieving the targets.

48 Price, O., & Bradstock, R. A. (2011). Quantifying the influence of fuel age and weather on the annual extent of unplanned fires in the Sydney region of Australia. *International Journal of Wildland Fire*, *20*(1), 142–151. https://doi.org/10.1071/WF10016

Planned fire is used globally to minimise the risk of unplanned fire, but it is important to measure the return for effort in terms of the reduction of risk per unit area of planned fire. Here, we use 30 years of fire mapping from four subregions of the Sydney region to compare the annual extent of unplanned fire with previous planned and unplanned fire. Using linear mixed modelling, we were able to discriminate the relative influence of previous fire, seasonal rainfall and weather during the peak fire season. The mean annual area burnt over the period was 4.11%, comprising 0.53% planned and 3.58% unplanned. We found that weather during the fire season was the most influential factor. Annual rainfall had a modest negative relationship with unplanned fire area. Past fire had some influence, but the relationship implied that approximately three units of planned fire are required to reduce the unplanned fire area by one unit. Managers would need to burn 5.4% per year to halve unplanned fire extent, a ten-fold increase on recent levels. This would increase the total area burnt, and have other effects that need to be considered (from smoke and greenhouse gas emissions, and changes to biodiversity).

49 Price, O., & Forehead, H. (2021). Smoke Patterns around Prescribed Fires in Australian Eucalypt Forests, as Measured by Low-Cost Particulate Monitors. *Atmosphere*, *12*(11), 1389–. https://doi.org/10.3390/atmos12111389

Prescribed burns produce smoke pollution, but little is known about the spatial and temporal pattern because smoke plumes are usually small and poorly captured by State air-quality networks. Here, we sampled smoke around 18 forested prescribed burns in the Sydney region of eastern Australia using up to 11 Nova SDS011 particulate sensors and developed a Generalised Linear Mixed Model to predict hourly $PM_{2.5}$ concentrations as a function of distance, fire size and weather conditions. During the day of the burn, $PM_{2.5}$ tended to show hourly exceedances (indicating poor air quality) up to ~2 km from the fire but only in the downwind direction. In the evening, this zone expanded to up to 5 km and included upwind areas. $PM_{2.5}$ concentrations were higher in still, cool weather and with an unstable atmosphere. $PM_{2.5}$ concentrations were also higher in larger fires. The statistical model confirmed these results, identifying the effects of distance, period of the day, wind angle, fire size, temperature and C-Haines (atmospheric instability). The model correctly identified 78% of hourly exceedance and 72% of non-exceedance values in retained test data. Applying the statistical model predicts that prescribed burns of 1000 ha can be expected to cause air quality exceedances over an area of ~3500 ha. Cool weather that reduces the risk of fire escape, has the highest potential for polluting nearby communities, and fires that burn into the night are particularly bad.

50 Price, O., Horsey, B., & Jiang, N. (2016). Local and regional smoke impacts from prescribed fires. *Natural Hazards and Earth System Sciences Discussions*, 1–20. https://doi.org/10.5194/nhess-2016-66

Smoke from wildfires poses a significant threat to affected communities. Prescribed burning is conducted to reduce the extent and potential damage of wildfires, but produces its own smoke threat. Planners of prescribed fires model the likely dispersion of smoke to help manage the impacts on local communities. Significant uncertainty remains about the actual smoke impact from prescribed fires, especially near the fire, and the accuracy of smoke dispersal models. To address this uncertainty, a detailed study of smoke dispersal was conducted for one small (52ha) and one large (700ha) prescribed fire near Appin in New South Wales, Australia, through the use of stationary and handheld pollution monitors, visual observations and rain radar data, and by comparing observations to predictions from an atmospheric dispersion model. The 52ha fire produced a smoke plume about 800m high and 9km long. Particle concentrations ($PM_{2.5}$) reached very high peak values (> 400µg m^{-3}) and high 24h average values (> 100µg m^{-3}) at several locations next to or within ~ 500m downwind from the fire, but low levels elsewhere. The 700ha fire produced a much larger plume, peaking at ~ 2000m altitude and affecting downwind areas up to 14km away. Both peak and 24h average $PM_{2.5}$ values near the fire were lower than for the 52ha fire, but this may be because the monitoring locations were further away from the fire. Some lofted smoke spread north against the ground-level wind direction. Smoke from this fire collapsed to the ground during the night at different times in different locations. Although it is hard to attribute particle concentrations definitively to smoke, it seems that the collapsed plume affected a huge area including the towns of Wollongong, Bargo, Oakdale, Camden and Campbelltown (~ 1200km^2). $PM_{2.5}$ concentrations up to 169 µg m^{-3} were recorded on the morning following the fire. The atmospheric dispersion model accurately predicted the general behaviour of both plumes in the early phases of the fires, but was poor at predicting fine-scale variation in particulate concentrations (e.g. places 500m from the fire). The correlation between predicted and observed varied between 0 and 0.87 depending on location. The model also completely failed to predict the night-time collapse of the plume from the 700ha fire. This study provides a preliminary insight into the potential for large impacts from prescribed fire smoke to NSW communities and the need for increased accuracy in smoke dispersion modelling. More research is needed to better understand when and why such impacts might occur and provide better predictions of pollution risk.

51 **Price, O., Mikac, K., Wilson, N., Roberts, B., Critescu, R., Gallagher, R., Mallee, J., Donatiou, P., Webb, J., Keith, D., Letnic, M., & Mackenzie, B. (2022). Short-term impacts of the 2019-20 fire season on biodiversity in eastern Australia. *Austral Ecology, 48,* 3-11. https://doi.org/10.1111/aec.13247**

To address uncertainties surrounding the impacts of unprecedented 2019– 20 bushfires in south-eastern Australia, we convened a symposium on field measured impacts on biodiversity for the 2020 Ecological Society of Australia conference. Nine presentations covered a range of studies on plant species and communities, and reptiles and mammals. Here, we summarize the presentations and review other field studies from NSW, some of which are currently unpublished. The impacts were extensive, but results also estimated survival rate perhaps higher than first reported in the media. More than half of individual mammal, reptile and threatened rainforest trees may have survived the fire, though small populations remain very vulnerable to second fire in the near future. Comprehensive understanding of the impacts of these fires requires much more field study, and for the results to be interpreted in the context of the broader fire regime. The symposium was an important early step in that understanding.

52 **Price, O., Nolan, R. H., & Samson, S. A. (2022). Fuel consumption rates in resprouting eucalypt forest during hazard reduction burns, cultural burns and wildfires. *Forest Ecology and Management*, *505*, 119894–. https://doi.org/10.1016/j.foreco.2021.119894**

Accurate estimation of emissions from biomass burning and their impact on carbon storage requires pre and post-fire plot measurement of fuel consumption across a range of forest types and fire severities, and this information is currently far from comprehensive in Australia or elsewhere. We measured fine and coarse fuels in 44 sites before and after 20 fires including cultural burns, hazard reduction burns and wildfires in resprouting dry sclerophyll (eucalypt) forests in the Sydney region of Australia. We compared consumption among the classes of fire severity and fire types. Most of the fires removed the great majority of fine litter and near surface fuels (mean 68% and 94% respectively) but a smaller and more variable percentage of other fine components and coarse fuels. Consumption was largely a function of pre-fire fuel levels. However, percentage consumption varied according to fire severity. Remaining fuel was negatively, and fresh fuel (i.e. immediate post-fire inputs) positively related to fire severity so that the two were in balance for litter, twigs and coarse woody debris. A higher proportion of twigs and coarse woody debris were consumed in hazard reduction and wildfires than in cultural burns, and more canopy and tree wood was consumed in wildfire than the other fire types. Total fuel consumption was 12.8 t ha^{-1} (13% of pre-fire) in cultural burns, 75.7 t ha^{-1} (27%) in hazard reductions, and 123.5 t ha^{-1} (38%) in wildfires. This was dominated by tree biomass consumption (69% of total). Our estimates for hazard reduction burns are higher than most previous studies from Australian forests, probably because our fires spanned a greater range of severities. Our study provides a benchmark for estimating fire emissions and carbon dynamics for the region and will contribute to improving predictions of the impact of hazard reduction burns on fire behaviour and smoke emissions.

53 **Price, O., Penman, T., Bradstock, R., & Borah, R. (2016). The drivers of wildfire enlargement do not exhibit scale thresholds in southeastern Australian forests. *Journal of Environmental Management*, *181*, 208–217. https://doi.org/10.1016/j.jenvman.2016.06.033**

Wildfires are complex adaptive systems, and have been hypothesized to exhibit scale-dependent transitions in the drivers of fire spread. Among other things, this makes the prediction of final fire size from conditions at the ignition difficult. We test this hypothesis by conducting a multi-scale statistical modelling of the factors determining whether fires reached 10 ha, then 100 ha then 1000 ha and the final size of fires >1000 ha. At each stage, the predictors were measures of weather, fuels, topography and fire suppression. The objectives were to identify differences among the models indicative of scale transitions, assess the accuracy of the multi-step method for predicting fire size (compared to predicting final size from initial conditions) and to quantify the importance of the predictors. The data were 1116 fires that occurred in the eucalypt forests of New South Wales between 1985 and 2010. The models were similar at the different scales, though there were subtle differences. For example, the presence of roads affected whether fires reached 10 ha but not larger scales. Weather was the most important predictor overall, though fuel load, topography and ease of suppression all showed effects. Overall, there was no evidence that fires have scale-dependent transitions in behaviour. The models had a predictive accuracy of 73%, 66%, 72% and 53% accuracy at 10 ha, 100 ha, 1000 ha and final size scales. When these steps were combined, the overall accuracy for predicting the size of fires was 62%, while the accuracy of the one step model was only 20%. Thus, the multi-scale approach was an improvement on the single scale approach, even though the predictive accuracy was probably insufficient for use as an operational tool. The analysis has also provided further evidence of the important role of weather, compared to fuel, suppression and topography in driving fire behaviour.

54 Price, O., Purdam, P. J., Williamson, G. J., & Bowman, D. M. J. S. (2018). Comparing the height and area of wild and prescribed fire particle plumes in south-east Australia using weather radar. *International Journal of Wildland Fire*, *27*(8), 525–537. https://doi.org/10.1071/WF17166

Smoke pollution from landscape fires is a major health issue. Prescribed burning aims to reduce the area and impact of wildfire, but itself produces smoke pollution. This raises the question as to whether the smoke production and transport from prescribed fires is substantially different compared to wildfires. We examined the maximum height, width and areal footprint of large-particle plumes from 97 wild and 126 prescribed fires in south-eastern Australia using the existing network of weather radars. Radar detects large particles in smoke (probably those >100 mm) and hence is an imperfect proxy for microfine (<2 mm) particles that are known to affect human health. Of the 223 landscape fires ~45% of plumes were detected, with the probability being >0.8 for large fires (>100 000 ha) regardless of type, closer than 50 km from the radar. Plume height was strongly influenced by fire area, the height of the planetary boundary layer and fire type. Plume heights differed between wildfire (range 1016–12 206 m, median 3260 m) and prescribed fires (range 706–6397 m, median 1669 m), and prescribed fires were predicted to be 800–1200 m lower than wildfires, controlling for other factors. For both wildfires and prescribed fires, the maximum plume footprint was always near the ground.

55 Price, O., Rahmani, S., & Samson, S. (2023). Particulate Levels Underneath Landscape Fire Smoke Plumes in the Sydney Region of Australia. *Fire, 6.* https://doi.org/10.3390/fire6030086

Smoke pollution from landscape fires is a major health problem, but it is difficult to predict the impact of any particular fire. For example, smoke plumes can be mapped using remote sensing, but we do not know how the smoke is distributed in the air-column. Prescribed burning involves the deliberate introduction of smoke to human communities but the amount, composition, and distribution of the pollution may be different to wildfires. We examined whether mapped plumes produced high levels of particulate pollution (PM2.5) at permanent air quality monitors and factors that influenced those levels. We mapped 1237 plumes, all those observed in 17 years of MODIS imagery over New South Wales, Australia, but this was only ~20% of known fires. Prescribed burn plumes tended to occur over more populated areas than wildfires. Only 18% of wildfire plumes and 4% of prescribed burn plumes passed over a monitor (n = 115). A minority of plumes caused a detectable increase in PM2.5: prescribed burn plumes caused an air quality exceedance for 33% of observations in the daytime and 11% at night, wildfire plumes caused exceedances for 48% and 22% of observations in the day and night-time, respectively. Thus, most plumes remained aloft (did not reach the surface). Statistical modelling revealed that wind speed, temperature, and mixing height influenced whether a plume caused an exceedance, and there was a difference between prescribed and wild fires. In particular, in wind speeds below 1 kmhr−1 , exceedance was almost certain in prescribed burns. This information will be useful for planning prescribed burning, preparing warnings, and improving our ability to predict smoke impacts.

56 Price, O., & Roberts, B. (2022). The role of construction standards on building impact of the 2013 Linksview Wildfire, Australia. *Fire Safety Journal, 128*. https://doi.org/10.1016/j.firesaf.2022.103545

The 2013 Linksview fire destroyed 195 houses in the Blue Mountains of NSW in 2013. In this study, we examined the role of construction codes on the impact of houses exposed to the fire, by extracting details of construction year and standard for 466 houses from the archives of the Blue Mountains City Council. Houses built to standards imposed from 2000 fared better than previous standards, though post-2000 houses assessed at Flame Zone level were vulnerable. Construction year was also a good predictor of impact with pre1990 houses suffering more than twice the level of impact as post-2000 houses. Older houses tended to have more vegetation within 10 m of the house, and this probably partly explains why they are more vulnerable. Year of modification (i.e. additions to a house) was a worse predictor than year of construction suggesting that imposing strict standards on modifications does not change the vulnerability of the whole house. We briefly discuss four policy implications of the study: Construction standards are clearly useful; Houses in the Flame Zone are vulnerable; Lack of maintenance is a problem; and Construction Standards for building modifications do not improve the resilience of the house.

57 Price, O., Williamson, G. J., Henderson, S. B., Johnston, F., & Bowman, D. M. J. S. (2012). The Relationship between Particulate Pollution Levels in Australian Cities, Meteorology, and Landscape Fire Activity Detected from MODIS Hotspots. *PloS One*, *7*(10), e47327–. https://doi.org/10.1371/journal.pone.0047327

Smoke from bushfires is an emerging issue for fire managers because of increasing evidence for its public health effects. Development of forecasting models to predict future pollution levels based on the relationship between bushfire activity and current pollution levels would be a useful management tool. As a first step, we use daily thermal anomalies detected by the MODIS Active Fire Product (referred to as "hotspots"), pollution concentrations, and meteorological data for the years 2002 to 2008, to examine the statistical relationship between fire activity in the landscapes and pollution levels around Perth and Sydney, two large Australian cities. Resultant models were statistically significant, but differed in their goodness of fit and the distance at which the strength of the relationship was strongest. For Sydney, a univariate model for hotspot activity within 100 km explained 24% of variation in pollution levels, and the best model including atmospheric variables explained 56% of variation. For Perth, the best radius was 400 km, explaining only 7% of variation, while the model including atmospheric variables explained 31% of the variation. Pollution was higher when the atmosphere was more stable and in the presence of on-shore winds, whereas there was no effect of wind blowing from the fires toward the pollution monitors. Our analysis shows there is a good prospect for developing region-specific forecasting tools combining hotspot fire activity with meteorological data.

58 Reisen, F., Bhujel, M., & Leonard, J. (2014). Particle and volatile organic emissions from the combustion of a range of building and furnishing materials using a cone calorimeter. *Fire Safety Journal*, *69*, 76–88. https://doi.org/10.1016/j.firesaf.2014.08.008

A series of experimental small-scale fire tests using a cone calorimeter were conducted. The objective of the tests was to provide a comparative assessment of particle and volatile organic compound emissions from the combustion of 10 commonly used types of building and furnishing materials relative to radiata pine, a dominant construction material. The materials tested included wood-based products (particle board, particle board with melamine surface finishes, medium-density fibreboard, painted pine), wool/nylon carpet, polyester insulation, two types of polyurethane (PUR) foams, high density polystyrene with cladding material and plasterboard. Tests were run at two irradiance levels, 25 kW m^{-2} and 50 kW m^{-2} under well-ventilated conditions. Samples were collected for analysis of gravimetric mass, particulate organic and elemental carbon, polycyclic aromatic hydrocarbons (PAHs), carbonyls and volatile organic compounds along with continuous measurements of carbon monoxide (CO), carbon dioxide (CO_2) and fine particles ($PM_{2.5}$). Under the tested conditions of flaming combustion of 11 materials, the highest pollutant concentrations per mass of specimen burnt resulted from the combustion of polyester insulation, polystyrene with cladding material, PUR foam and a wool/nylon carpet. Among wood-based materials, medium-density fibreboard and particle board with melamine surface ranked highest in emissions, with pine ranking lowest. However, wood-based products make up the majority of mass in building structures so that emissions from wood-based products may contribute more significantly to total emissions and hence to exposures than emissions from the polymeric materials.

59 Resco de Dios, V., Fellows, A. W., Nolan, R. H., Boer, M. M., Bradstock, R. A., Domingo, F., & Goulden, M. L. (2015). A semi-mechanistic model for predicting the moisture content of fine litter. *Agricultural and Forest Meteorology*, *203*(C), 64–73. https://doi.org/10.1016/j.agrformet.2015.01.002

The moisture content of vegetation and litter (fuel moisture) is an important determinant of fire risk, and predictions of dead fine fuel moisture content (fuel with a diameter <25.4 mm) are particularly important. A variety of indices, as well as empirical and mechanistic models, have been proposed to predict fuel moisture, but these approaches have seldom been validated across temporally extensive datasets, or widely contrasting vegetation types. Here, we describe a semi-mechanistic model, based on the exponential decline of fuel moisture content with atmospheric vapor pressure deficit, that predicts daily minimum fuel moisture content. We calibrated the model at one site in New South Wales, Australia, and validated it at three contrasting ecosystem types in California, USA, where 10-h fuel moisture content was continuously measured every 30 min over a year. We found that existing drought indices did not accurately predict fuel moisture, and that empirical and equilibrium models provided biased estimates. The mean absolute error (MAE) of the fuel moisture content predicted by our model across sites and years was 3.7%, which was substantially lower than for other, commonly used models. Our model's MAE dropped to 2.9% when fuel moisture was below 20%, and to 1.8% when fuel moisture was below 10%. Our model's MAE was comparable to instrumental MAE (3.1–2.5%), indicating that further improvement may be limited by measurement error. The simplicity, accuracy and precision of our model makes it suitable for a range of applications, such as operational fire management and the prediction of fire risk in vegetation models, without the need for site-specific calibrations.

60 Ryan, R., Dosseto, A., Lemarchand, D., Dlapa, P., Thomas, Z., Simkovic, I., & Bradstock, R. (2023). Boron isotopes and FTIR spectroscopy to identify past high severity fires. *Catena, 222,* https://doi.org/10.1016/j.catena.2022.106887

Bushfires have played a crucial role in shaping the landscape and biodiversity for millennia. As fire regimes continue to alter with climate change, greater understanding becomes critical in mediating future events. Existing records are largely historically limited or do not accurately identify fire severity; therefore, there is a need to develop new proxies that can extend our fire records significantly. Here, we test whether changes in carbon (C) and nitrogen (N) content, boron (B) isotopes and Fourier Transform Infrared (FTIR) spectra in sediment deposits can identify past fire events. To achieve this, we investigated sediments deposited in small order creek beds of the Upper Nepean Catchment in southeastern Australia. In each deposit, layers associated with past fire events were independently identified based on visual inspection of higher charcoal abundance. Radiocarbon dating of charcoal fragments was used to approximate the age of the fire events. Neither C and N abundances nor C/N ratios show association with charcoal-rich layers, suggesting they are not useful proxies to identify past fires. Conversely, FTIR spectra show increased aromatic/aliphatic ratios in sediment layers recording past fire events. This observation suggests that those fires were hot enough to reduce long chain aliphatic compounds to more temperature- and decomposition-resistant aromatics. In each deposit, an increase in δ11B by 2–7 ‰ is associated with charcoal-rich sediment layers. Leaves and fine branches, which burn only during high severity fires, are enriched in 11B, possibly causing the increase in the δ11B value of the sediment clay size fraction. These results suggest that, even in these small order creek beds which are typically transient environments, both FTIR spectra and B isotopes are potentially useful proxies to identify past fire events.

61 Simpson, H., Bradstock, R., & Price, O. (2019). A temporal framework of large wildfire suppression in practice, a qualitative descriptive study. *Forests*, *10*(10), 884–. https://doi.org/10.3390/f10100884

Suppression activities on large wildfires are complicated. Existing suppression literature does not take into account this complexity which leaves existing suppression models and measures of resource productivity incomplete. A qualitative descriptive analysis was performed on the suppression activities described in operational documents of 10 large wildfires in Victoria, Australia. A five-stage classification system summarises suppression in the everyday terms of wildfire management. Suppression can be heterogeneous across different sectors with different stages occurring across sectors on the same day. The stages and the underlying 20 suppression tasks identified provide a fundamental description of how suppression resources are being used on large wildfires. We estimate that at least 57% of resource use on our sample of 10 large wildfires falls outside of current suppression modelling and productivity research.

62 Simpson, H., Bradstock, R., & Price, O. (2021). Quantifying the Prevalence and Practice of Suppression Firing with Operational Data from Large Firest in Victoria, Australia. *Fire, 4.* https://doi.org/10.3390/fire4040063

Fire management agencies around the world use suppression firing for fire control. Yet, we know little about the extent of its use (e.g., prevalence and spatial coverage) and its impact on containment. We examine the prevalence and practice of suppression firing in Victoria, Australia. We used operational data from five years (2010–2015) to identify and map the incidence of suppression firing on 74 large fires (500+ ha). Suppression firing occurred on half (34) of these fires, 26 of which had data to map firing locations. The area burnt by suppression firing ranged from < 1 ha to ~20,000 ha on separate fires. Archetypal suppression firing occurred during intervals of low fire spread and resulted in modest fire behaviour. Ground crews generally conducted the perimeter suppression firing. Aerial ignition was more common on large internal firing operations. For the 26 fires where we mapped the firing locations, firing occurred along 77% of the perimeter-aligned road. Suppression firing was a prominent containment tool used along one-fifth of the total external perimeter of these 74 large fires. Quantification of this practice is a first step towards establishing ignition thresholds, production rates, and integration with containment probability models.

63 Storey, M., Bedward, M., Price, O. F., Bradstock, R. A., & Sharples, J. J. (2021). Derivation of a Bayesian fire spread model using large-scale wildfire observations. Environmental Modelling & Software : with Environment Data News, 144, 105127–. https://doi.org/10.1016/j.envsoft.2021.105127

Models that predict wildfire rate of spread (ROS) play an important role in decision-making during firefighting operations, including fire crew placement and timing of community evacuations. Here, we use a large set of remotely sensed wildfire observations, and explanatory data (focusing on weather), to demonstrate a Bayesian probabilistic ROS modelling approach. Our approach has two major advantages: (1) Using actual wildfire observations, instead of controlled fire observations, makes models developed well-suited to wildfire prediction; (2) Bayesian modelling accounts for the complex nature of wildfire spread by explicitly considering uncertainty in the data to produce probabilistic ROS predictions. We show that highly informative probabilistic predictions can be made from a simple

Bayesian model containing wind speed, relative humidity and soil moisture. We provide current operational context to our work by calculating predictions from widely used deterministic ROS models in Australia.

64 Storey, M., & Price, O. (2022). Prediction of air quality in Sydney, Australia as a function of forest fire load and weather using Bayesian statistics. *PLOS One, 17(8).* https://doi.org/10.1371/journal.pone.0272774

Smoke from Hazard Reduction Burns (HRBs) and wildfires contains pollutants that are harmful to human health. This includes particulate matter less than 2.5 μm in diameter (PM2.5), which affects human cardiovascular and respiratory systems and can lead to increased hospitalisations and premature deaths. Better models are needed to predict PM2.5 levels associated with HRBs so that agencies can properly assess smoke pollution risk and balance smoke risk with the wildfire mitigation benefits of HRBs. Given this need, our aim was to develop a probabilistic model of daily PM2.5 using Bayesian regression. We focused on the region around Sydney, Australia, which regularly has hazard reduction burning, wildfires and associated smoke. We developed two regional models (mean daily and maximum daily) from observed PM2.5, weather reanalysis and satellite fire hotspot data. The models predict that the worst PM2.5 in Sydney occurs when PM2.5 was high the previous day, there is low ventilation index (i.e. the product of wind speed and planetary boundary layer height), low temperature, west to northwest winds in the Blue Mountains, an afternoon sea breeze and large areas of HRBs are being conducted, particularly to the west and north of Sydney. A major benefit of our approach is that models are fast to run, require simple inputs and Bayesian predictions convey both predicted PM2.5 and associated prediction uncertainty. Future research could include the application of similar methods to other regions, collecting more data to improve model precision and developing Bayesian PM2.5 models for wildfires.

65 Storey, M., & Price, O. (2022). Statistical modelling of air quality impacts from individual forest fires in New South Wales, Australia. *Natural Hazards and Earth System Sciences, 22,* 4039-4062. https://doi.org/10.5194/nhess-22-4039-2022

Wildfires and hazard reduction burns produce smoke that contains pollutants including particulate matter. Particulate matter less than 2.5 μm in diameter (PM2.5) is harmful to human health, potentially causing cardiovascular and respiratory issues that can lead to premature deaths. PM2.5 levels depend on environmental conditions, fire behaviour and smoke dispersal patterns. Fire management agencies need to understand and predict PM2.5 levels associated with a particular fire so that pollution warnings can be sent to communities and/or hazard reduction burns can be timed to avoid the worst conditions for PM2.5 pollution. We modelled PM2.5, measured at air quality stations in New South Wales (Australia) from ~ 1400 d when individual fires were burning near air quality stations, as a function of fire and weather variables. Using Visible Infrared Imaging Radiometer Suite (VIIRS) satellite hotspots, we identified days when one fire was burning within 150 km of at least 1 of 48 air quality stations. We extracted ERA5 gridded weather data and daily active fire area estimates from the hotspots for our modelling. We created random forest models for afternoon, night and morning PM2.5 levels to understand drivers of and predict PM2.5. Fire area and boundary layer height were important predictors across the models, with temperature, wind speed and relative humidity also being important. There was a strong increase in PM2.5 with decreasing distance, with a sharp increase when the fire was within 20 km. The models improve our understanding of the drivers of PM2.5 from individual fires and demonstrate a promising approach to PM2.5 model development. However, although the models predicted well overall, there were several large under-predictions of PM2.5 that mean further model development would be required for the models to be deployed operationally.

66 Storey, M., Price, O. F., Almeida, M., Ribeiro, C., Bradstock, R. A., & Sharples, J. J. (2021). Experiments on the influence of spot fire and topography interaction on fire rate of spread. *PloS One*, *16*(1), e0245132–e0245132. https://doi.org/10.1371/journal.pone.0245132

Spotting is thought to increase wildfire rate of spread (ROS) and in some cases become the main mechanism for spread. The role of spotting in wildfire spread is controlled by many factors including fire intensity, number of and distance between spot fires, weather, fuel characteristics and topography. Through a set of 30 laboratory fire experiments on a 3 m x 4 m fuel bed, subject to air flow, we explored the influence of manually ignited spot fires (0, 1 or 2), the presence or absence of a model hill and their interaction on combined fire ROS (i.e. ROS incorporating main fire and merged spot fires). During experiments conducted on a flat fuel bed, spot fires (whether 1 or 2) had only a small influence on combined ROS. Slowest combined ROS was recorded when a hill was present and no spot fires were ignited, because the fires crept very slowly downslope and downwind of the hill. This was up to, depending on measurement interval, 5 times slower than ROS in the flat fuel bed experiments. However, ignition of 1 or 2 spot fires (with hill present) greatly increased combined ROS to similar levels as those recorded in the flat fuel bed experiments (depending on spread interval). The effect was strongest on the head fire, where spot fires merged directly with the main fire, but significant increases in off-centre ROS were also detected. Our findings suggest that under certain topographic conditions, spot fires can allow a fire to overcome the low spread potential of downslopes. Current models may underestimate wildfire ROS and fire arrival time in hilly terrain if the influence of spot fires on ROS is not incorporated into predictions.

67 Thomas, P., Watson, P. J., Bradstock, R. A., Penman, T. D., & Price, O. F. (2014). Modelling surface fine fuel dynamics across climate gradients in eucalypt forests of south-eastern Australia. *Ecography (Copenhagen)*, *37*(9), 827–837. https://doi.org/10.1111/ecog.00445

An understanding of the effects of climate on fuel is required to predict future changes to fire. We explored the climatic determinants of variations in surface fine fuel parameters across forests (dry and wet sclerophyll plus rainforest) and grassy woodlands of south-eastern Australia. Influences of vegetation type and climate on fuel were examined through statistical modelling for estimates of litterfall, decomposition and steady state fine litter fuel load obtained from published studies. Strong relationships were found between climate, vegetation type and all three litter parameters. Litterfall was positively related to mean annual rainfall and mean annual temperature across all vegetation types. Decomposition was both negatively and positively related to mean annual temperature at low and high levels of warm-season rainfall respectively. Steady state surface fine fuel load was generally, negatively related to mean annual temperature but mean annual rainfall had divergent effects dependent on vegetation type: i.e. positive effect in low productivity dry sclerophyll forests and grassy woodlands versus negative effect in high productivity wet sclerophyll forests and rainforests. The species composition of the vegetation types may have influenced decomposition and steady state fuel load responses in interaction with climate: e.g. lower decomposition rates in the low productivity vegetation types that occupied drier environments may be partially due to the predominance of species with sclerophyllous leaves. The results indicate that uncertain and highly variable future trends in precipitation may have a crucial role in determining the magnitude and direction of change in surface fine fuel load across south-eastern Australia.

68 Wang, B., Spessa, A., Feng, P., Hou, X., Yue, C., Luo, JJ., Ciais, P., Waters, C., Cowie, A., Nolan, R., Nikonovas, T., Jin, H., Walshaw, H., Wei, J., Guo, X., Liu, D., & Yu, Q. (2022). Extreme fire weather is the major driver of severe bushfires in southeast Australia. *Science Bulletin, 67,* 655-664. https://doi.org/10.1016/j.scib.2021.10.001

In Australia, the proportion of forest area that burns in a typical fire season is less than for other vegetation types. However, the 2019–2020 austral spring-summer was an exception, with over four times the previous maximum area burnt in southeast Australian temperate forests. Temperate forest fires have extensive socio-economic, human health, greenhouse gas emissions, and biodiversity impacts due to high fire intensities. A robust model that identifies driving factors of forest fires and relates impact thresholds to fire activity at regional scales would help land managers and fire-fighting agencies prepare for potentially hazardous fire in Australia. Here, we developed a machine-learning diagnostic model to quantify nonlinear relationships between monthly burnt area and biophysical factors in southeast Australian forests for 2001–2020 on a 0.25 grid based on several biophysical parameters, notably fire weather and vegetation productivity. Our model explained over 80% of the variation in the burnt area. We identified that burnt area dynamics in southeast Australian forest were primarily controlled by extreme fire weather, which mainly linked to fluctuations in the Southern Annular Mode (SAM) and Indian Ocean Dipole (IOD), with a relatively smaller contribution from the central Pacific El Niño Southern Oscillation (ENSO). Our fire diagnostic model and the non-linear relationships between burnt area and environmental covariates can provide useful guidance to decision-makers who manage preparations for an upcoming fire season, and model developers working on improved early warning systems for forest fires.

69 Wilson, N., Bradstock, R., & Bedward, M. (2022). Disturbance causes variation in sub-canopy fire weather conditions. *Agricultural and Forest Meteorology, 323*. https://doi.org/10.1016/j.agrformet.2022.109077

Disturbance history is known to affect fire risk by altering fuel dynamics, but the effects of disturbance on micrometeorological conditions that influence fire are poorly understood. Logging and wildfire can significantly alter the height and density of vegetation in forests. These structural attributes can influence aspects of the sub-canopy microclimate that may influence forest flammability. We used portable weather stations to measure the effects of time since logging and time since wildfire on air temperature, relative humidity, vapour pressure deficit and windspeed at 119 sites in coastal forest in south-eastern Australia. These data were used to calculate fuel moisture and within forest Forest Fire Danger Index (FFDI). Data were collected on 345 days (12 days per site on average), over three consecutive fire seasons. Temperature, vapour pressure deficit, windspeed and forest FFDI all decreased with time since logging, while relative humidity and fuel moisture content increased. Windspeeds also decreased with time since wildfire. These effects continued for at least 60 years after disturbance. Over the duration of our study, fuel was available to burn (below 16% fuel moisture content) 1.4 times more often in recently logged sites (zero years since logging) compared to sites that had not been logged for 71 years. Recently logged sites were also predicted to have a high Fire Danger Rating (FFDI = 12–24) on 24 days, compared to just two days at sites last logged 71 years ago. Our findings indicate that the changes in vegetation associated with logging and to a lesser extent wildfire, increase the risk of fire. This research provides new insights into the effects of antecedent logging and wildfire on forest flammability that can be used to inform the management of fire prone forests.

70 Wilson, N., Bradstock, R., & Bedward, M. (2022). Influence of fuel structure derived from terrestrial laser scanning (TLS) on wildfire severity in logged forests. *Journal of Environmental Management, 302.* https://doi.org/10.1016/j.envman.2021.114011

Context: Logging and wildfire can reduce the height of the forest canopy and the distance to the understorey vegetation below. These conditions may increase the likelihood of high severity wildfire (canopy scorch or consumption), which may explain the greater prevalence of high severity wildfire in some recently logged or burnt forests. However, the effects of these structural characteristics on wildfire severity have not clearly been demonstrated. Objectives: We aimed to assess how the structure of forests affected by logging and wildfire influence the probability of high severity wildfire. Methods: We used terrestrial laser scanning to measure the connectivity of canopy and understorey vegetation in forests at various stages of recovery after logging and wildfire (approximately 0–80 years since disturbance). These sites were subsequently burnt by mixed severity wildfire during the 2019–20 ‘Black Summer’ fire season in south-eastern Australia. We assessed how these forest structure metrics affected the probability of high severity wildfire. Results: The probability of high severity fire decreased as the canopy base height increased, and the distance between the canopy base and understorey increased. High severity wildfire was less likely in forests with taller understoreys and greater canopy or understorey cover, but these effects were not considered causal. Fire weather was the strongest driver of wildfire severity, which was also affected by topography. Conclusions: These findings demonstrate a link between forest structure characteristics, that are strongly shaped by antecedent logging and fire, and fire severity. They also indicate that vertical fuel structure should be incorporated into assessments of fire risk.

71 Wilson, N., & Bradstock, R. (2022). Past Logging and Wildfire Increase above Ground Carbon Stock Losses from Subsequent Wildfire. *Fire, 5.* https://doi.org/10.3390/fire5010026

Wildfire is known to reduce forest carbon stocks, but the influence of antecedent disturbance on wildfire related carbon stock losses is not as well understood. Disturbances such as logging and wildfire may increase the vulnerability of remaining carbon stocks to subsequent wildfire. Conversely, these disturbances may reduce the impact of subsequent wildfire, resulting in lower carbon stock losses. Methods: We measured above ground carbon stocks in productive resprouting Eucalypt dominated forests before and after a mixed severity fire that burned during the 2019/20 ‘Black Summer’ fire season in south-eastern Australia. The initial surveys were stratified by time since logging and time since wildfire, allowing for an assessment of how these disturbance histories influence above ground carbon stock losses caused by subsequent wildfire. Results: Above ground carbon stock losses varied substantially; however, there was a weak decrease in losses associated with time since logging but not time since wildfire. Variance in carbon stock losses associated with logging were greater than that caused by the severity of the 2019/20 wildfire itself. Carbon losses and predicted effects of disturbance may be underestimated in some cases due to the accumulation of carbon at sites between pre- and post-fire surveys. Conclusions: This study presents the largest published dataset of direct carbon stock changes resulting from wildfire in eucalypt forests. Our findings indicate that logging reduces the stability of above ground carbon stocks in resprouting eucalypt forests. This information will be critical for land managers looking to manage forests for carbon sequestration.

72 Zhu, Q., Yang, X., Yu, B., Tulau, M., McInnes-Clarke, S., Nolan, R. H., Du, Z., & Yu, Q. (2019). Estimation of event-based rainfall erosivity from radar after wildfire. *Land Degradation & Development*, *30*(1), 33–48. https://doi.org/10.1002/ldr.3146

Rainfall erosivity impacts all stages of hillslope erosion processes and is an important factor (the ‘R factor’) in the Revised Universal Soil Loss Equation. It is estimated as the average annual value of the sum of all erosive events (EI_{30}) over a period of many years. For each storm event, the EI_{30} value is the product of storm energy, E in MJ ha^{-1}, and peak 30-min rainfall intensity (I_{30}, mm hr^{-1}). Previous studies often focused on estimation of the R factor for prediction of mean annual or long-term soil losses. However, many applications require EI_{30} values at much higher temporal resolution, such as postfire soil erosion monitoring, which requires a time step at storm events or on a daily basis. In this study, we explored the use of radar rainfall data to estimate the storm event-based EI_{30} after a severe wildfire in Warrumbungle National Park in eastern Australia. The radar-derived rainfall data were calibrated against 12 tipping bucket rain gauges across an area of 239 km^2 and subsequently used to produce a time series of rainfall erosivity maps at daily intervals since the wildfire in January 2013. The radar-derived daily rainfall showed good agreement with the gauge measurements (R^2 > 0.70, E_c = 0.66). This study reveals great variation in EI_{30} values ranging from near zero to 826.76 MJ·mm·ha^{-1}·hr^{-1} for a single storm event. We conclude that weather radar rainfall data can be used to derive timely EI_{30} and erosion information for fire incident management and erosion control. The methodology developed in this study is generic and thus readily applicable to other areas where weather radar data are available.

73 Zylstra, P., Bradstock, R. A., Bedward, M., Penman, T. D., Doherty, M. D., Weber, R. O., Gill, A. M., & Cary, G. J. (2016). Biophysical mechanistic modelling quantifies the effects of plant traits on fire severity: Species, not surface fuel loads, determine flame dimensions in eucalypt forests. *PloS One*, *11*(8), e0160715–e0160715. https://doi.org/10.1371/journal.pone.0160715.

The influence of plant traits on forest fire behaviour has evolutionary, ecological and management implications, but is poorly understood and frequently discounted. We use a process model to quantify that influence and provide validation in a diverse range of eucalypt forests burnt under varying conditions. Measured height of consumption was compared to heights predicted using a surface fuel fire behaviour model, then key aspects of our model were sequentially added to this with and without species-specific information. Our fully specified model had a mean absolute error 3.8 times smaller than the otherwise identical surface fuel model ($p < 0.01$), and correctly predicted the height of larger (≥1 m) flames 12 times more often ($p < 0.001$). We conclude that the primary endogenous drivers of fire severity are the species of plants present rather than the surface fuel load, and demonstrate the accuracy and versatility of the model for quantifying this.

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