NSW Bushfire Risk Management Research Hub

Burning for a healthy future: People and their environments

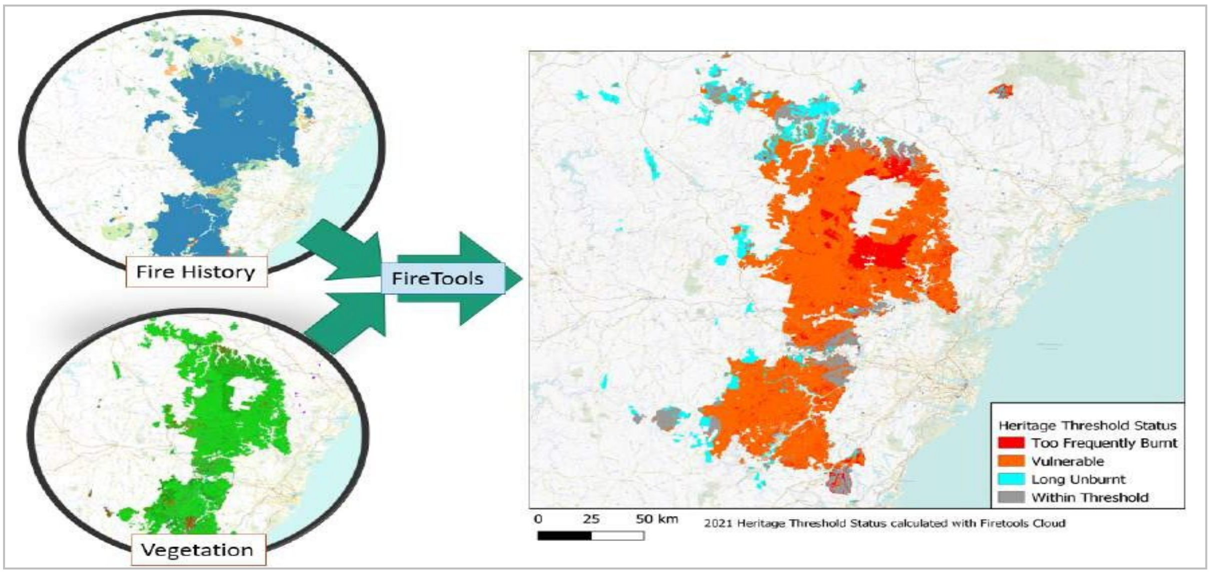
NSW Bushfire Risk Management Research Hub

Work Package Synopses

Western Sydney University · UNSW Sydney · University of Tasmania Australia · University of Wollongong Australia · NSW Government

Contents

Work Package 1: Dynamic mapping and analysis of NSW fire regimes



Research team

Work was conducted by Chief Investigator Professor David Bowman and Lead Researcher Dr Grant Williamson from the University of Tasmania Fire Centre. Their team included Stephanie Samson, Owen Price, and Ross Bradstock from the University of Wollongong, and PhD student Todd Ellis from the University of Tasmania. Key agency collaborators included Rebecca Gibson (DCCEW), Andrew Denham (DCCEW), Liz Tasker, Freya Gordon (Parks), Navneil Nadan (National Parks and Wildlife, NPWS)), Brenton Marchant (NPWS), Stephen Parker (NPWS), as well as hub researchers Rachael Nolan (WSU), Matthias Boer (WSU), Hamish Clark (UOW), David Keith and Mark Ooi (UNSW), Kat Haynes, and Fay Johnston Nicolas Borchers-Arriagada (UTAS).

Overview

Work package 1 had a range of outputs of broad relevance to the fire regimes of New South Wales, and incorporated research extending in scope beyond the geographic bounds of NSW. The FireTools project developed a cloud-based GIS processing environment for fire regime analysis, allowing the rapid calculation of vegetation threshold status based on vegetation fire intervals and fire history. This tool was later extended to the SDC high performance computing environment, to enable timeseries analysis of regime, and associated landscape metrics, useful for establishing baseline ecosystem state, and deviations in fire regime. FireTools continues to be used frequently operationally, and further enhancements are planned through the NSW Bushfire and Natural Hazards Research Centre.

The work package also contributed significantly to the 2019/2020 bushfire inquiry report, performing analyses of the relative impact of past land management practices and fire weather on fire severity across the significant are impacted. This work identified the relatively short-lived impact of hazard reduction burning on fire severity under elevated fire weather conditions, and the relative importance of fire weather conditions in driving severity despite hazard reduction operations. This research led to several high-impact publications. Related publications stemming from the bushfire inquiry report addressed the global definition of megafires and long-term impacts of megafires on carbon stocks, a study which produced the first accurate estimate of the atmospheric carbon emissions from the Black Summer fires. The work package also collaborated with work package 2 in developing an online real-time map of fuel moisture dynamics, and work package 3 in assessing the human health costs of the Black Summer fires.

Finally, this work package incorporated a student project investigating drivers of fire regime change, which was global in scope but which includes analysis relevant to NSW, highlighting long-term trends in declining fuel moisture. Papers currently in-press identify distinct fuel moisture thresholds across NSW, and the potential for seasonal shifts in the core fire season.

Aims

To develop an efficient method for the automated measurement and monitoring of fire regimes through the confluence of multiple data streams that will be processed and stored in a searchable geographic information database.

Projects and outcomes

FireTools Cloud

Different plant species and communities have a characteristic fire regime associated with them – the optimal combination of fire intensity, season, and frequency and patch size. Fires that occur outside the bounds of this template can affect biodiversity and other natural values, leading to long-term or irreversible ecosystem change. Some systems, such as dry *Eucalyptus* forests, benefit from frequent fire (on the order of decades), others such wet *Eucalyptus* forests require longer return times between fires to enable persistence, while other systems such as rainforests are sensitive to fire, and any fire that occurs is likely to cause long-term damage or state shift. Associated with the issue of optimal fire interval is fuel build-up – after a fire, which consumes fuels, fuel gradually builds up towards an equilibrium point which varies between systems, and planning for fire management requires an understanding of how frequently prescribed and hazard reduction burning should target an area to preserve ecological values and to reduce fuel loads.

Work Package 1 was tasked with modernizing a fire regime management proprietary GIS tool (FireTools) used by NSW Parks & Wildlife Service to map and analyse the status of vegetation based on fire regime attributes and fire history. We developed a cloud-based processing system (FireTools Cloud) using open source frameworks (R, Node, GDAL), that enables managers to upload files defining fire history, vegetation community maps, and fire attributes to the web, and download processed maps of vegetation status to assist in prescribed burn planning, along with maps of fire frequency and time since fire.

Vegetation is categorized into four classes (Long Unburnt, Within Threshold, Vulnerable and Too Frequently Burnt) based on the community fire regime attributes and fire history. Class is calculated from heuristics associated with the number of times a community has been burnt at an interval less than the minimum fire interval, and the time since fire. Figure 1.1 shows example FireTools Cloud output for eastern NSW before and after the 2019/2020 fire season, indicating large areas have shifted into a vulnerable state where additional fire may cause ecological state shift.

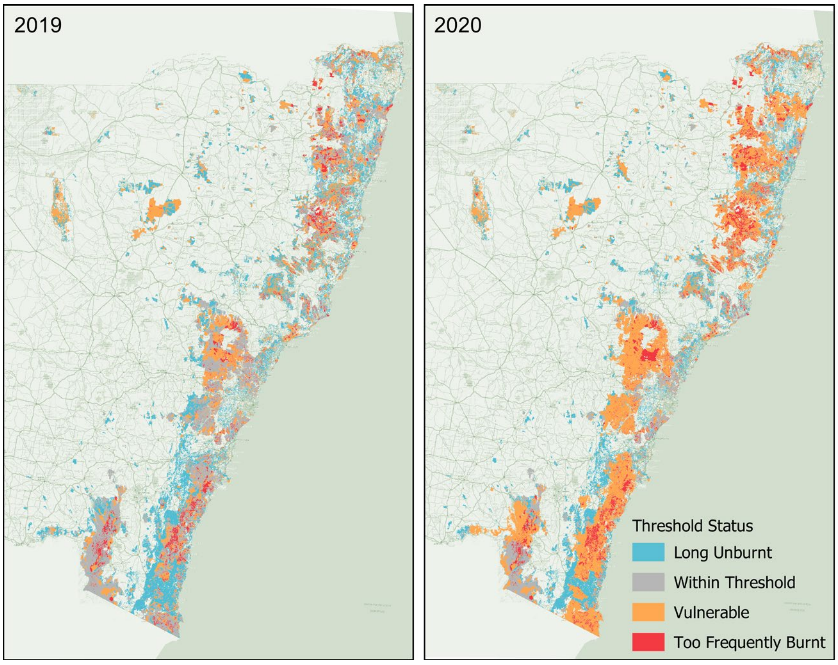


Figure 1.1. FireTools Cloud vegetation threshold status for 2019 and 2020 across eastern New South Wales.

FireTools SDC

After the release of FireTools Cloud, the need was identified for more advanced processing of vegetation regime status, to enable analysis of timeseries of data; producing a map and statistical summary for each year over time, so the temporal patterns of vegetation state over time could be seen, and the impacts of significant fire years identified. A version of FireTools was developed to run on the NSW Government SDC (Science Data Compute) high-performance computing system.

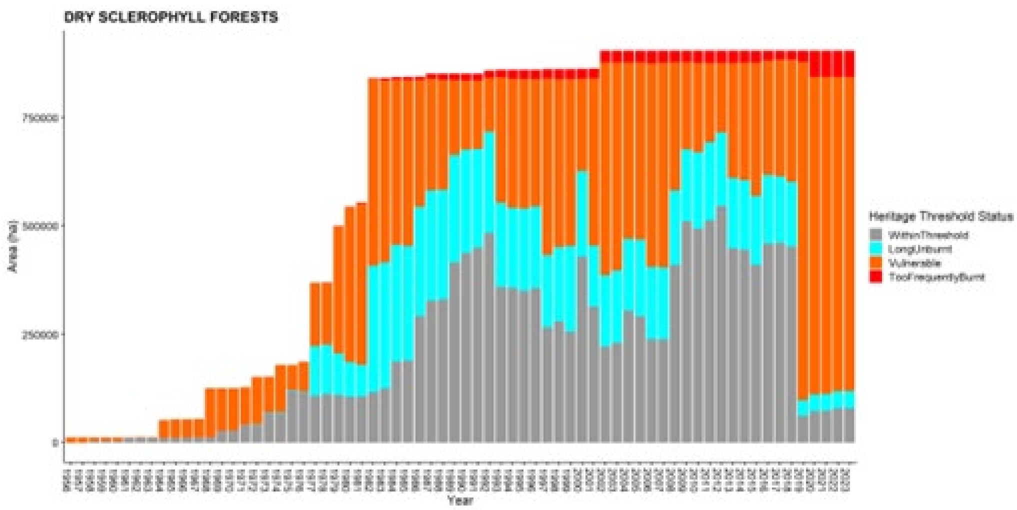


Figure 1.2. FireTools SDC timeseries analysis of vegetation status in Dry Sclerophyll Forests in the Blur Mountains across time.

FireTools SDC leveraged the parallel processing available on this environment to achieve processing speeds 50 to 100 times faster than the initial FireTools Cloud product, and many of these efficiencies were then integrated into FireTools Cloud. Analysis improvement built into FireTools Cloud included rapid pre-processing of vegetation and fire history data, processing of annual timeseries of vegetation status (Figure 1.2) and time since fire, summaries by vegetation formation, integration of the outputs of the FESM (Fire Extent and Severity Mapping) product, and calculation of landscape metrics across the time series, which provide indices of the spatial arrangement of vegetation status: whether patches are highly clustered, widely dispersed, intermixed or clumped. Figure 1.3 shows example output from the Euclidean Nearest Neighbour distance calculation for patch status, showing a sharp increase in the mean distance between long-unburnt patches following the 2019/2020 fires.

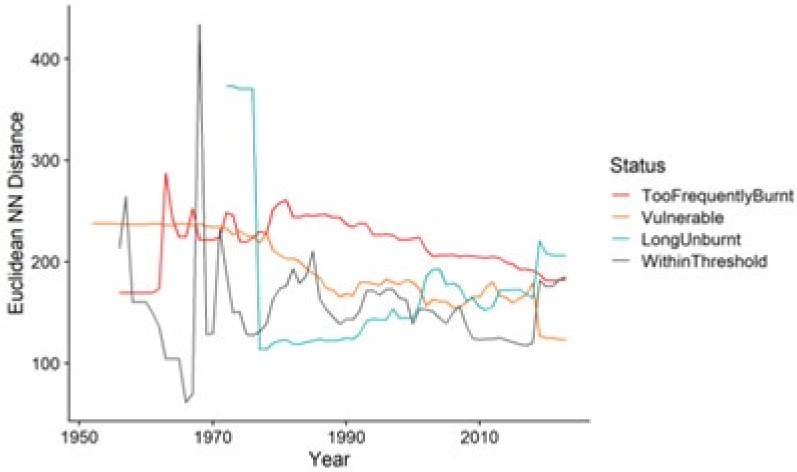


Figure 1.3. FireTools SDC Timeseries of patch nearest neighbour distance.

2019/2020 Bushfire Inquiry

Work Package 1 contributed to the NSW Bushfire Inquiry into the disastrous 2019/2020 fire season, producing four reports studying questions of fire progression and weather, and patterns of fire severity in relation to past fire, weather, and land use. We conducted a detailed geospatial analysis of fire severity in relation to these drivers using detailed satellite-derived severity metrics, and concluded that there while was no detectable effect of past fire severity on severity during the recent fires, there was evidence recent fire in the past reduced the probability of severe fire, this effect was short lived (5-10 years) and hazard reduction burns had limited ability to reduce fire severity under more extreme fire weather conditions (Figure 1.4). This work led to contributions to a number of publications, including an assessment of the relevance of logging to fire severity across south-eastern Australian fires.

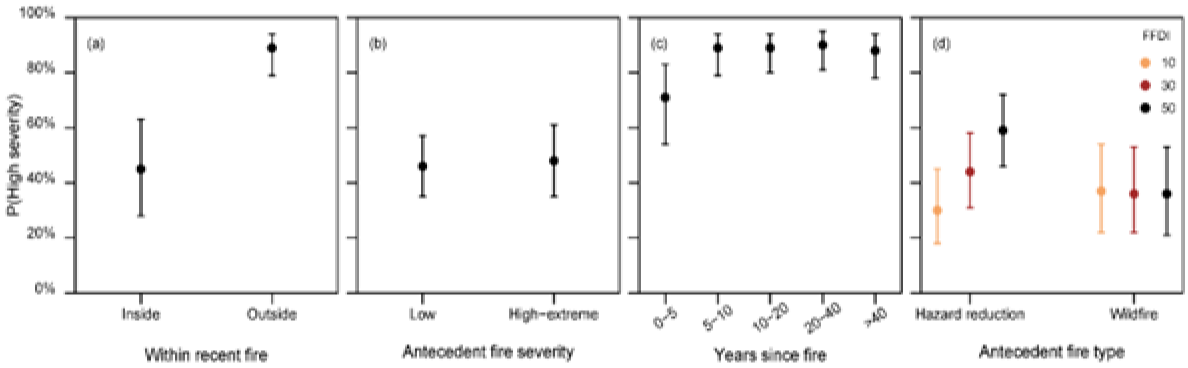


Figure 1.4. Analysis of probability of fire severity fire in the 2019/2020 fire season in relation to the presence of past fire, the severity of past fire, the time since past fire, and the fire weather conditions.

Fuel Moisture Trends

Work Package 1 PhD student Todd Ellis conducted research into the fuel moisture threshold component of fire regimes, identifying that the moisture content at which fuel can support fire spread varies between ecosystems and vegetation types. This analysis was based, initially, on a global-scale climate reanalysis and burnt area dataset, identified local thresholds of dead fuel moisture content associated with elevated fire activity, and used those thresholds to track trends in fuel moisture in the recent climate record, to identify regions around the globe undergoing significant drying trends. Australian ecosystems showed a less significant drying trend than other regions, likely due to the strong cyclical, ENSO-driven pattern driving precipitation (Figure 1.5).

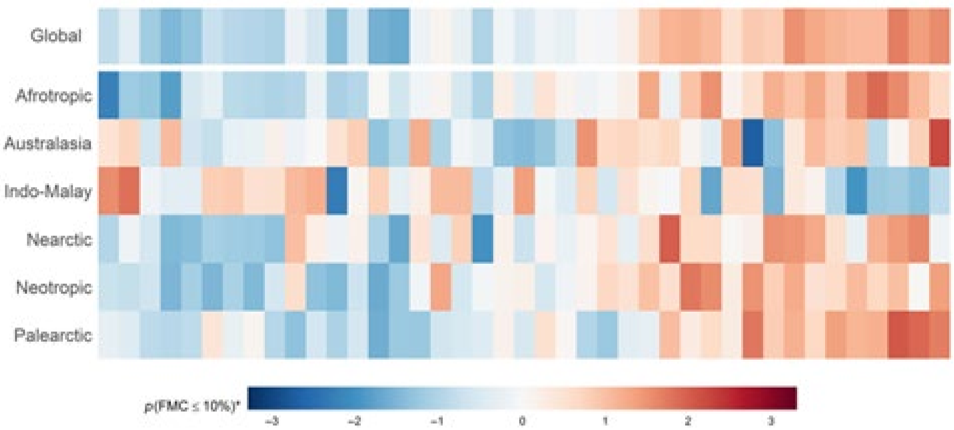


Figure 1.5.Mean trend patterns for fire season proportions falling under a 10% fuel moisture content (FMC) threshold. Each time series shows anomalies relative to its climatological mean.

Key Outputs

Linley, G. D., Jolly, C. J., Doherty, T. S., Geary, W. L., Armenteras, D., Belcher, C. M., ... & Nimmo, D. G. Williamson G.J. et al. (2022). **What do you mean, 'megafire'?** *Global Ecology and Biogeography*.

> '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.
>
> 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.
>
> 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).
>
> 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.

Le Breton, T. D., Lyons, M. B., Nolan, R. H., Penman, T., Williamson, G. J., & Ooi, M. K. (2022). **Megafire-induced interval squeeze threatens vegetation at landscape scales.** *Frontiers in Ecology and the Environment*. 20(5) 327-334.

> 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 south-eastern 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.

Nolan, R. H., Bowman, D. M., Clarke, H., Haynes, K., Ooi, M. K., Price, O. F., Williamson, G. J. & Bradstock, R. A. (2021). **What do the Australian black summer fires signify for the global fire crisis?** *Fire*, *4*(4), 97.

The 2019–20 Australian fire season was heralded as emblematic of the catastrophic harm wrought by climate change. Similarly extreme wildfire seasons have occurred across the globe in recent years. Here, we apply a pyrogeographic lens to the recent Australian fires to examine the range of causes, impacts and responses. We find that the extensive area burnt was due to extreme climatic circumstances. However, antecedent hazard reduction burns (prescribed burns with the aim of reducing fuel loads) were effective in reducing fire severity and house loss, but their effectiveness declined under extreme weather conditions. Impacts were disproportionately borne by socially disadvantaged regional communities. Urban populations were also impacted through prolonged smoke exposure. The fires produced large carbon emissions, burnt fire-sensitive ecosystems and exposed large areas to the risk of biodiversity decline by being too frequently burnt in the future. We argue that the rate of change in fire risk delivered by climate change is outstripping the capacity of our ecological and social systems to adapt. A multi-lateral approach is required to mitigate future fire risk, with an emphasis on reducing the vulnerability of people through a reinvigoration of community-level capacity for targeted actions to complement mainstream fire management capacity.

Bowman, D. M., Williamson, G. J., Gibson, R. K., Bradstock, R. A., & Keenan, R. J. (2021). **The severity and extent of the Australia 2019–20 Eucalyptus forest fires are not the legacy of forest management**. *Nature Ecology & Evolution*, *5*(7), 1003-1010.

> The 2019–20 wildfires in eastern Australia presented a globally important opportunity to evaluate the respective roles of climatic drivers and natural and anthropogenic disturbances in causing high-severity fires. Here, we show the overwhelming dominance of fire weather in causing complete scorch or consumption of forest canopies in natural and plantation forests in three regions across the geographic range of these fires. Sampling 32% (2.35 Mha) of the area burnt we found that >44% of the native forests suffered severe canopy damage. Past logging and wildfire disturbance in natural forests had a very low effect on severe canopy damage, reflecting the limited extent logged in the last 25 years (4.5% in eastern Victoria, 5.3% in southern New South Wales (NSW) and 7.8% in northern NSW). The most important variables determining severe canopy damage were broad spatial factors (mostly topographic) followed by fire weather. Timber plantations affected by fire were concentrated in NSW and 26% were burnt by the fires and >70% of the NSW plantations suffered severe canopy damage showing that this intensive means of wood production is extremely vulnerable to wildfire. The massive geographic scale and severity of these Australian fires is best explained by extrinsic factors: an historically anomalous drought coupled with strong, hot dry westerly winds that caused uninterrupted, and often dangerous, fire weather over the entire fire season.

Ellis, T. M., Bowman, D. M., Jain, P., Flannigan, M. D., & Williamson, G. J. (2022). **Global increase in wildfire risk due to climate-driven declines in fuel moisture.** *Global change biology*, *28*(4), 1544-1559.

> There is mounting concern that global wildfire activity is shifting in frequency, intensity, and seasonality in response to climate change. Fuel moisture provides a powerful means of detecting changing fire potential. Here, we use global burned area, weather reanalysis data, and the Canadian fire weather index system to calculate fuel moisture trends for multiscale biogeographic regions across a gradient in vegetation productivity. We quantify the proportion of days in the local fire season between 1979 and 2019, where fuel moisture content is below a critical threshold indicating extreme fire potential. We then associate fuel moisture trends over that period to vegetation productivity and comment on its implications for projected anthropogenic climate change. Overall, there is a strong drying trend across realms, biomes, and the productivity gradient. Even where a wetting trend is observed, this often indicates a trend toward increasing fire activity due to an expected increase in fuel production.

The detected trends across the productivity gradient lead us to conclude global fire activity will increase with anthropogenic climate change.

Bowman, D. M., Williamson, G. J., Price, O. F., Ndalila, M. N., & Bradstock, R. A. (2021). **Australian forests, megafires and the risk of dwindling carbon stocks.** *Plant, Cell & Environment*, *44*(2), 347-355.

Over the Austral spring and summer of 2019/20 > 7 million ha of *Eucalyptus* forest and woodland, including some of Australia's most carbon dense ecosystems, were burnt on the east coast of Australia. We estimated bootstrapped mean CO_2 emissions of c. 0.67 Pg, with other available estimates ranging from 0.55 to 0.85 Pg. *Eucalyptus* forests are renowned for their ability to resist and recover from wildfire so it would be expected that emitted CO_2 will be reabsorbed. The combination of drought and frequent fires is likely reducing the capacity to recover from the fire so future Australian forests may store less carbon. Broadscale prescribed burning is a widely promoted approach to reduce uncontrolled wildfires, yet the benefits for the management of carbon stores are controversial. Prescribed burning can reduce carbon losses from subsequent wildfire, yet the “carbon costs” of it may equal or outweigh the “carbon benefits” in reduced wildfire emissions. Likewise, mechanical thinning of vegetation to reduce fuel loads also carries heavy carbon costs with uncertain carbon benefits. Research involving empirical measurements, modelling and a mix of large-scale management intervention is urgently required to determine what interventions can maximise carbon storage in the face of climate change-driven fires.

Bowman, D., Williamson, G., Yebra, M., Lizundia-Loiola, J., Pettinari, M. L., Shah, S., ... & Chuvieco, E. (2020). **Wildfires: Australia needs national monitoring agency**. *Nature* 584, 188-191

Just before the COVID-19 pandemic, bush fires in Australia destroyed more than 3,000 homes and burnt millions of hectares of vegetation. The crisis exposed the nation’s fire monitoring system as being unfit for purpose. Precise real-time information about the area burnt and the intensity of the fires was not available when it was needed.

Australia does not have a central system for gathering and storing essential information about bush fires. State and territory governments, and even agencies within states, have different approaches. This worked fine when fires were smaller. But those in the 2019–20 season crossed multiple state borders.

Johnston, F. H., Borchers-Arriagada, N., Morgan, G. G., Jalaludin, B., Palmer, A. J., Williamson, G. J., & Bowman, D. M. (2021). **Unprecedented health costs of smoke-related PM2.5 from the 2019–20 Australian megafires**. *Nature Sustainability*, *4*(1), 42-47.

> In flammable landscapes around the globe, longer fire seasons with larger, more severely burnt areas are causing social and economic impacts that are unsustainable. The Australian 2019–20 fire season is emblematic of this trend, burning over 8 million ha of predominately *Eucalyptus* forests over a six-month period. We calculated the wildfire-smoke-related health burden and costs in Australia for the most recent 20 fire seasons and found that the 2019–20 season was a major anomaly in the recent record, with smoke-related health costs of AU$1.95 billion. These were driven largely by an estimated 429 smoke-related premature deaths in addition to 3,230 hospital admissions for cardiovascular and respiratory disorders and 1,523 emergency attendances for asthma. The total cost was well above the next highest estimate of AU$566 million in 2002–03 and more than nine times the median annual wildfire associated costs for the previous 19 years of AU$211 million. There are substantial economic costs attributable to wildfire smoke and the potential for dramatic increases in this burden as the frequency and intensity of wildfires increase with a hotter climate.

Full publications list

Adeleye, MA, Haberle, SG, Bowman, D (2023) Long-term stability of temperate Australian wet forest-moorland mosaics despite recurrent fires associated with late Holocene climate change. *Landscape Ecology*

Adeleye, MA, Haberle, SG, Connor, SE, Stevenson, J, Bowman, D (2021) Indigenous Fire-Managed Landscapes in Southeast Australia during the Holocene-New Insights from the Furneaux Group Islands, Bass Strait. *Fire-Switzerland* **4**,

Adeleye, MA, Haberle, SG, Ondei, S, Bowman, D (2022) Ecosystem transformation following the mid-nineteenth century cessation of Aboriginal fire management in Cape Pillar, Tasmania. *Regional Environmental Change* **22**,

Bowman, D (2021) Conflagrations and the Wisdom of Aboriginal Sacred Knowledge. *Fire-Switzerland* **4**,

Bowman, D (2023) Detecting, Monitoring and Foreseeing Wildland Fire Requires Similar Multiscale Viewpoints as Meteorology and Climatology. *Fire-Switzerland* **6**,

Bowman, D, Bliss, A, Bowman, CJW, Prior, LD (2019) Fire caused demographic attrition of the Tasmanian palaeoendemic conifer Athrotaxis cupressoides. *Austral Ecology* **44**, 1322-1339.

Bowman, D, French, B, Williamson, GJ, Prior, LD (2021) Fire, herbivores and the management of temperate Eucalyptus savanna in Tasmania: Introducing the Beaufront fire -

mammalian herbivore field experiment. *Ecological Management & Restoration* **22**, 140-151.
Bowman, D, Furlaud, JM, Porter, M, Williamson, GJ (2022) The Fuel Moisture Index Based on Understorey Hygrochron iButton Humidity and Temperature Measurements Reliably Predicts Fine Fuel Moisture Content in Tasmanian Eucalyptus Forests. *Fire-Switzerland* **5**,
Bowman, D, Kolden, CA, Abatzoglou, JT, Johnston, FH, van der Werf, GR, Flannigan, M (2020) Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment* **1**, 500-515.
Bowman, D, Moreira-Munoz, A, Kolden, CA, Chavez, RO, Munoz, AA, Salinas, F, Gonzalez-Reyes, A, Rocco, R, de la Barrera, F, Williamson, GJ, Borchers, N, Cifuentes, LA, Abatzoglou, JT, Johnston, FH (2019) Human-environmental drivers and impacts of the globally extreme 2017 Chilean fires. *Ambio* **48**, 350-362.
Bowman, D, Ondei, S, Lucieer, A, Foyster, S, Prior, LD (2023) Forest-sedgeland boundaries are historically stable and resilient to wildfire at Blakes Opening in the Tasmanian Wilderness World Heritage Area, Australia. *Landscape Ecology* **38**, 205-222.
Bowman, D, Ondei, S, Nichols, SC, Foyster, SM, Prior, LD (2023) Fire Cycles and the Spatial Pattern of the Scrub-Sedgeland Mosaic at Blakes Opening in Western Tasmania, Australia. *Fire-Switzerland* **6**,
Bowman, D, Williamson, G, Yebra, M, Lizundia-Loiola, J, Pettinari, ML, Shah, S, Bradstock, R, Chuvieco, E (2020) Wildfires: Australia needs national monitoring agency. *Nature* **584**, 188-191.
Bowman, D, Williamson, GJ (2021) River Flows Are a Reliable Index of Forest Fire Risk in the Temperate Tasmanian Wilderness World Heritage Area, Australia. *Fire-Switzerland* **4**,
Bowman, D, Williamson, GJ, Gibson, RK, Bradstock, RA, Keenan, RJ (2021) The severity and extent of the Australia 2019-20 Eucalyptus forest fires are not the legacy of forest management. *Nature Ecology & Evolution* **5**, 1003-+.
Bowman, D, Williamson, GJ, Johnston, FH, Bowman, CJW, Murphy, BP, Roos, CI, Trauernicht, C, Rostron, J, Prior, LD (2022) Population collapse of a Gondwanan conifer follows the loss of Indigenous fire regimes in a northern Australian savanna. *Scientific Reports* **12**,
Bowman, D, Williamson, GJ, Price, OF, Ndalila, MN, Bradstock, RA (2021) Australian forests, megafires and the risk of dwindling carbon stocks. *Plant Cell and Environment* **44**, 347-355.
Cochrane, MA, Bowman, D (2021) Manage fire regimes, not fires. *Nature Geoscience* **14**, 455-457.
Crisp, MD, Cook, LG, Bowman, D, Cosgrove, M, Isagi, Y, Sakaguchi, S (2019) Turnover of southern cypresses in the post-Gondwanan world: extinction, transoceanic dispersal, adaptation and rediversification. *New Phytologist* **221**, 2308-2319.

Ellis, TM, Bowman, D, Jain, P, Flannigan, MD, Williamson, GJ (2022) Global increase in wildfire risk due to climate-driven declines in fuel moisture. *Global Change Biology* **28**, 1544-1559.

Lucas, CH, Williamson, GJ, Bowman, D (2022) Neighbourhood bushfire hazard, community risk perception and preparedness in peri-urban Hobart, Australia. *International Journal of Wildland Fire* **31**, 1129-1143.

McCormack, PC, McDonald, J, Eburn, M, Little, SJ, Bowman, D, Harris, RMB (2022) AN ANATOMY OF AUSTRALIA'S LEGAL FRAMEWORK FOR BUSHFIRE. *Melbourne University Law Review* **46**, 156-217.

Ndalila, MN, Williamson, GJ, Bowman, D (2022) Carbon dioxide and particulate emissions from the 2013 Tasmanian firestorm: implications for Australian carbon accounting. *Carbon Balance and Management* **17**,

Ndalila, MN, Williamson, GJ, Fox-Hughes, P, Sharples, J, Bowman, D (2020) Evolution of a pyrocumulonimbus event associated with an extreme wildfire in Tasmania, Australia. *Natural Hazards and Earth System Sciences* **20**, 1497-1511.

Reid, AM, Murphy, BP, Vigilante, T, Barry, LA, Bowman, D, Wunambal Gaambera Aboriginal, C (2020) Carbon isotope analysis shows introduced bovines have broader dietary range than the largest native herbivores in an Australian tropical savanna. *Austral Ecology* **45**, 109-121.

Reid, AM, Murphy, BP, Vigilante, T, Bowman, D, Wunambal Gaambera Aboriginal, C (2020) Distribution and abundance of large herbivores in a northern Australian tropical savanna: A multi-scale approach. *Austral Ecology* **45**, 529-547.

Reid, AM, Murphy, BP, Vigilante, T, Bowman, D, Wunambal Gaambera Aboriginal, C (2023) Pyric Herbivory and the Nexus Between Forage, Fire and Native and Introduced Large Grazing Herbivores in Australian Tropical Savannas. *Ecosystems* **26**, 610-626.

Roos, CI, Williamson, GJ, Bowman, D (2019) Is Anthropogenic Pyrodiversity Invisible in Paleofire Records? *Fire-Switzerland* **2**,

Williamson, GJ, Ellis, TM, Bowman, D (2022) Double-Differenced dNBR: Combining MODIS and Landsat Imagery to Map Fine-Grained Fire MOSAICS in Lowland Eucalyptus Savanna in Kakadu National Park, Northern Australia. *Fire-Switzerland* **5**,

Work package 2 – Fuel, flammability and carbon dynamics

Research Team

Rachael Nolan, Kathryn Fuller, Anne Griebel, Christopher Gordon and Matthias Boer

Overview

Work package 2 (WP2) developed biophysical modelling frameworks and protocols to predict spatiotemporal variation in fuel (i.e. flammable vegetation) load, composition, structure, accumulation and flammability within vegetation and fuel types of New South Wales (NSW). The work package also developed methods to quantify fire impacts on ecosystem level carbon storage. These objectives were achieved using field survey data, high-resolution remote sensing, existing flora data bases and models of vegetation growth, drought stress and post-fire recovery. Below, we describe some of the key advances made by WP2 across the funding period and overview the primary research outputs.

Additional research funding acquired by WP2

- Australian Research Council Linkage grant, 2020: "Forecasting live fuel moisture content, the on / off switch for forest fire". Awarded to Western Sydney University (administering organisation) in collaboration with the Australian National University, with industry partners NSW Department of Climate Change, Environment and Water (DCCEW), NSW Rural Fire Service and Australian Capital Territory Parks. The cash value of the grant is $910,997, with a total value of $1,671,799 inclusive of additional research from DCCEW and in-kind contributions. The project extended the work within WP2.4 by advancing the eco-physiological underpinning of the live fuel moisture modelling, and developing a more advanced forecasting system. This project is due for completion in the final quarter of 2024.
- Hermon Slade Foundation grant, 2020: "Quantifying forest mortality after unprecedented drought and bushfires in Eastern Australia". Awarded to Dr. Rachael Nolan (Western Sydney University). The cash value of the grant is $83,538, plus an additional $90,000 committed by Western Sydney University for a PhD stipend. The project funded an extensive field survey of post-fire tree mortality and drought mortality after the 2019/20 fires across a range of forest and woodland types in NSW, which directly relates to WP2.3.
- Early Career Research grant, Western Sydney University, 2019: Awarded to Dr. Rachael Nolan (Western Sydney University). The cash value of the grant is $18,518. The was used to assist with field work for Hub research, specifically relating to the work conducted in WP2.2. and WP2.3.

Aims

Fuels are one of the key drivers of fire behaviour. By investigating several kinds of fuel including fine fuels such as leaves and twigs, and woody fuels researchers seek to deepen understanding of how variability in these features affects fire. The overarching aim of this work package was to improve our understanding of the way bushfire fuels vary over time. In particular; how various fuel types are consumed by a bushfire, how fuel loads recover, and how these factors vary according to fire severity and vegetation type.

Projects and outcomes

WP2.1. Models of the composition of fuel forming components within broad vegetation types

The sub-package produced spatially explicit probabilistic models of fuel types using flora data bases, remote sensing products including aerial and satellite-based LiDAR and gridded environmental data on climate, terrain, and fire history. This work formed the core of the WSU-funded PhD by Kathryn Fuller and produced spatially explicit models of fuel type and structure across NSW. An overview of the work is described below:

WP2.1.- Project 1: Bark-type prediction: Tree bark-type is a strong driver of fire behaviour, particularly in terms of rates of fire spread and spotting; however, accurate state-wide bark-type maps were not available at the onset of the project. The project used tree species occurrence records from the BIONET database to classify hundreds of *Eucalyptus* species into 10 broad bark types. Machine learning Random Forest models were used to predict the spatial distribution of these bark types at fine resolutions as a function of vegetation formation, topography, climate and fire history. The project identified key drivers of bark-type distributions and produced fine-scale bark-fuel type maps which will be of use for fire behaviour prediction and prescribed fire management.

WP2.1.- Project 2: Remote sensing of fuel structure: Fuel structure (i.e. the 3D connectivity of fuels) influences many aspects of fire behaviour, particularly fire severity and the occurrence of canopy fires. Global Ecosystem Dynamics Investigation (GEDI) spaceborne LiDAR data products, which have only recently become available to the science community, were used to characterise the 3D structure of forest and woodland communities across NSW. A clustering technique was used to group geo-referenced canopy height profiles from individual GEDI LiDAR 'shots' into distinct structural classes. A Machine Learning approach was then used to predict the spatial distribution of these classes as a function of biophysical predictors. The project demonstrated the applicability (and great promise) of GEDI LiDAR data for fuel structure assessment across biogeographically diverse landscapes.

WP2.2. Models for the prediction of live and dead fuel accumulation dynamics

The sub-package used field-survey data, fuel load prediction models and fire simulations to understand reciprocal interactions between fire severity and fuel load. This work formed a component of the postdoctoral work of Dr. Rachael Nolan and Dr. Chris Gordon and was completed in collaboration with other members of the Bushfire Hub including Associate

Professor Owen Price (University of Wollongong). An overview of the work is described below:

WP2.2.- Project 1: Post-fire fuel load prediction: The "Olsen curve" is operationally used within NSW to predict fuel loads relative to rates of litter input / decay and post-fire fuel load (the amount of vegetation remaining immediately after fire). Post-fire fuel load is poorly represented in such models, and a better representation of this fuel parameter will result in better fuel predictions. The project used a field survey of fuel loads at 44 -sites before and after cultural burns, prescribed fires and wildfires to understand how burn-type and fire severity impacted post-fire fuel load. Fire severity was assessed in the field. The project showed pre-fire fuel load was the most important predictor of post-fire fuel load; however, fire severity and burn-type also had important effects. Percentage fuel consumption was generally higher at higher fire severities and for wildfire > prescribe fires > cultural burns. The study provides important benchmark information for fuel load prediction using methods such as the Olsen curve. Relevant academic publication: *Price et al, 2022, Forest Ecology and Management*.

WP2.2.- Project 2: Fuel load prediction and fire behaviour: Accurate fuel load prediction is required to better represent fire activity in fire behaviour models operationally. This study incorporated information on fire severity vs fuel load dynamics (*WP2.2.- Project 1*) into the existing Olson curve and compared fuel load predictions from this novel approach to the original one. The two sets of fuel load measurements were then used as inputs to predict fire activity within the fire behaviour model "Phoenix RapidFire". The project showed that accounting for burn heterogeneity, and fire severity effects on bark fuels, improved fire predictions. This has strong implications for operational risk estimation and evaluating the cost-effectiveness of planned burning programmes Relevant academic publication: *Nolan et al, in review, International Journal of Wildland Fire*.

WP2.2.- Project 3: Elevated (shrub) fuel load estimation: Accurate quantification of fine fuel load (typically foliage and twigs < 6 mm diameter) in forests is required for many fire behaviour models. However, current estimation methods poorly represent Elevated fine fuel loads (i.e. the shrub layer between the forest floor and tree canopy) because coarser material comprises a large portion of total biomass. This project developed allometric equations for shrubs that relate stem diameter to the portion of above-ground biomass comprised of fine fuel. The models were used to estimate elevated fine fuel loads before and after prescribed fires. The allometric equations accurately predicted fine fuel load, and the proportion of shrub biomass comprised of fine fuel varied from 6 to 58% in unburned forests. The proportion of fuel consumed by fire was also shown to vary considerably. The project provided models of shrub fine fuels which can be used to better predict fine fuel loads over large heterogeneous areas. Relevant academic publication: *Nolan et al, 2022, Forest Ecology and Management*.

WP2.2.- Project 4: Litter decomposition and standing fuel load: Litter decomposition / decay is a key factor affecting steady-state fuel load. A mechanistic understanding of processing impacts litter decomposition rates is required for accurate fuel load prediction using methods including the Olsen curve. However, our understanding of such processes is limited. This project aimed to understand how climate (which moderates litter decay), plant diversity (which inputs litter) and fungal diversity (which decays litter) impacted rates of leaf litter decomposition at 30-sites spread across a broad climatic gradient in the Sydney Basin bioregion. The field sites for this project were setup in late 2022 – early 2023, with the floristic and fungal surveys conducted in late 2022 and the litter decomposition experiment initiated in early 2023. This project is ongoing, and the litter decomposition experiment will end in early 2024. The results of the field survey will be used to "re-parameterise" the Olsen curve for better fuel load prediction.

WP2.3. Effects of wildfire on carbon stocks

The sub-package used field-survey data to quantify wildfire impacts on above ground carbon biomass and 3D structure and optimised equations for biomass estimation. This work formed a component of Kathryn Fullers PhD research and Dr. Rachael Nolan and Dr. Chris Gordon's postdoctoral work. An overview of the work is described below:

WP2.3.- Project 1: Fire severity impacts on above ground carbon: Wildfire can impact above ground carbon stocks by releasing sequestered carbon through combustion, redistributing carbon within vegetative elements, or selecting vegetation types that store more or less carbon. Little is known about how fire severity impacts carbon stocks, particularly in-terms of how tree mortality redistributes carbon from the "stable" live carbon pool to the "volatile" dead pool. This project used field survey data from four forest types of NSW to understand how fire severity impacts tree mortality and the re-distribution of carbon from the live to dead pool. Fire severity was associated with increased changes to carbon stocks between the live and dead carbon pools; however, there were marked differences among forest types. Specifically, the driest forest type had the highest rates of canopy top-kill following high severity fire. These results highlight the importance of spatial variability in fire severity and forest type in determining the effects of fire on carbon stocks. Relevant academic publication: *Nolan et al, 2022, Global Ecology and Biogeography*.

WP2.3.- Project 2: Fire severity impacts on fuel structure: Forest structure (i.e. 3D biomass distribution) is shaped by environmental processes such as wildfire and drought. It is critical to understand how wildfire and drought impacts forest structure to better predict potential changes in forest dynamics, including carbon storage. The LiDAR dataset from "*WP2.1-Project 2"* was used to determine how fire severity, drought stress, temperature and precipitation impacted post-fire forest structure and forest structure recovery rates over a 50-year period. The project showed high severity fire had greater impacts on forest structure than low severity fire and that drought stress resulted in poor post-fire recovery. The project provided key information that can be used to predict the stability of carbon stocks, both in terms of carbon storage and flux.

WP2.3.- Project 3: Shrub biomass estimation: Allometric equations, which relate vegetation biomass to simplistic field measurements (e.g. stem diameter), are a key tool to estimate carbon biomass and flux. Methods that accurately estimate biomass are key for carbon accounting for climate change mitigation. "*WP2.2-Project 3"* developed allometric equations to quantify shrub fuel loads; however, similar equations were also developed to assess overall biomass. The models provided a reliable method for shrub biomass estimation in forests of south-eastern NSW (when compared with destructively sampled biomass) and will provide an ideal method for carbon estimation within this carbon pool. Relevant academic publication: *Nolan et al, 2022, Forest Ecology and Management*.

WP2.3.- Project 4: Fire interval and severity - impacts on above ground carbon: In addition to the field survey conducted in *WP2.3.- Project 1*, Chris Gordon and collaborators within the Applied Bushfire Science Program (NSW DCCEW) initiated a similar assessment of ecosystem carbon estimation at 64-sites across the Sydney Basin Bioregion in 2022. The field survey was conducted 2-years after the 2019 / 20 wildfires (all sites were burned) and sites were stratified by differences in fire severity (high, low) and interval (of the proceeding fire; < 7-years, > 7-years). The project is ongoing and will provide a better understanding of how fire regimes impacts forest carbon stocks. The project will also add to a growing "database" of field sites were carbon estimations have been conducted using comparable methods (e.g. those made in *WP2.3.- Project 1 & 3, WP2.2.- Project 1*).

WP2.4- Prediction & forecasting of flammability

The sub-package developed spatially explicit methods for remote sensing and prediction of live and dead fuel moisture content. These models can be used to both identify critical landscape flammability thresholds and forecast landscape flammability across biogeographically diverse regions. This work formed a component of the postdoctoral work of Dr. Rachael Nolan and Dr Anne Griebel. An overview of the work is described below:

WP2.4.- Project 1: Forest flammability and plant vulnerability to drought: Current approaches to modelling forest flammability largely overlook plant vulnerability to drought. This project reviewed the literature on drought vs flammability interactions and outlined the mechanisms through which plant responses to drought may affect flammability, with a focus on fuel moisture and the ratio of dead to live fuels. The project presented a framework for modelling live fuel moisture content (moisture content of foliage and twigs) from soil water content and plant traits. It also presented evidence that physiological drought stress may contribute to previously observed fuel moisture thresholds in south-eastern Australia. The project suggested future avenues for research into drought vs flammability research, which were further explored in *WP2.4- Project 2 and 3*. Relevant academic publication: *Nolan et al, 2020, Forests*.

WP2.4.- Project 2: Live fuel moisture content prediction through pressure-volume curves: Large forest fires generally occur when fuel moisture content is low. For live fuel, 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. This project furthered our understanding of how these mechanisms drive spatiotemporal variations in LFMC through the development of "pressure-volume curves", which estimate LFMC by measuring leaf water potential and water content on dehydrating cut plant shoots. The derived LFMC models reliably predicted seasonal variation in LFMC across four co-occurring species. Further, across a large climatic gradient, the LFMC model was strongly correlated with specific leaf area and aridity. The project showed that spatiotemporal dynamics of LFMC are governed by leaf dry mass traits and the relationship between leaf water potential and water content, which suggest that incorporating these traits into spatiotemporal models of LFMC will improve wildfire danger forecasting. Relevant academic publication: *Nolan et al, 2022, Agriculture and Forest Management*.

WP2.4.- Project 3: Live fuel moisture content prediction from plant traits, hydrological status and climate: LFMC is an important precondition for wildfire activity, yet it remains challenging to predict due to the dynamic interplay between the atmospheric and hydrological conditions that determine plant's access to, and loss of water. This project combined plant traits, hydrological status and atmospheric variables into a biophysical model to predict LFMC dynamics, and compared predictions from this model to others derived from satellite data and pressure-volume curves. The biophysical model explained up to 89% of variability in LFMC and outperformed other approaches. Within the model, specific leaf area (which accounts for the dry mass of foliage) was the single most important variable to predict LFMC, followed by vapour pressure deficit (the atmospheric demand for water). The study provides an exciting "new way forward" for the accurate prediction of LFMC across vast spatial and temporal domains. Relevant academic publication: *Griebel et al, 2023, Functional Ecology*. This project is still continuing under the associated linkage grant (see further details below).

Key Outputs

Rachael Nolan was awarded a *Forests* 2020 Young Investigator of the Year Award, primarily for research undertaken for the Hub.

Full publications list

Peer-reviewed research papers from WP2

- Gordon, C.E., Boer, M.M., Griebel, A., Yebra, M., Sturgess, A., Collins, L. and Nolan, R.H. 2023. Fuel moisture moderates wildfire resistance in fire refugia. Geophyscial Research Letters, *In Review*.

- Nolan, R.H., Gibson, R.K., Cirulis, B., Holyland, B., Samson, S.A., Jenkins, M., Penman, T. and Boer, M.M. 2023. Incorporating fire severity and burn patchiness into fuel load estimates improves fire behaviour predictions. International Journal of Wildland Fire, *In Review*.
- Griebel, A., Boer, M.M., Blackman, C., Choat, B., Ellsworth, D.S., Madden, P., Medlyn, B., Resco de Dios, V., Wujeska-Klause, A., Yebra, M. and Younes Cardenas, N. 2023. Specific leaf area and vapour pressure deficit control live fuel moisture content. Functional Ecology. https://doi.org/10.1111/1365-2435.14271
- Nolan, R. H., Collins, L., Gibson, R. K., Samson, S. A., Rolls, K. T., Milner, K., Medlyn, B.E., Price, O.F., Griebel, A, Choat, B, Jiang, M and Boer, M. M. 2022. The carbon cost of the 2019–20 Australian fires varies with fire severity and forest type. Global Ecology and Biogeography 31(10), 2131-2146.
- Nolan, R.H., Foster, B., Griebel, A., Choat, B., Medlyn, B.E., Yebra, M., Younes Cardenas, N., Boer, M.M., 2022. Drought-related leaf functional traits control spatial and temporal dynamics of live fuel moisture content. Agricultural and Forest Meteorology 319, 108941.
- Price, O.H., Nolan, R.H. and 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.
- Nolan, R.H., 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.
- Nolan, R.H., Bowman, D.M.J.S., Clarke, H., Haynes, K., Ooi, M.K.J., Price, O.F., Williamson, G.J., Whittaker, J., Bedward, M., Boer, M.M., Cavanagh, V.I., Collins, L., Gibson, R.K., Griebel, A., Jenkins, M.E., Keith, D.A., Mcilwee, A.P., Penman, T.D., Samson, S.A., Tozer, M.G., Bradstock, R.A., 2021. What do the Australian Black Summer fires signify for the global fire crisis? Fire 4, 97.
- Nolan, R.H., Collins, L., Leigh, A., Ooi, M.K.J., Curran, T.J., Fairman, T.A., Resco de Dios, V., Bradstock, R., 2021. Limits to post-fire vegetation recovery under climate change. Plant, Cell & Environment 44, 3471– 3489.

1. Nolan, R.H., Gauthey, A., Losso, A., Medlyn, B.E., Smith, R., Chhajed, S.S., Fuller, K., Song, M., Li, X., Beaumont, L.J., Boer, M.M., Wright, I.J. and Choat, B. 2021. Hydraulic failure and tree size linked with canopy die-back in eucalypt forest during extreme drought. *New Phytologist* 230, 1354-1365.

2. Nolan, R.H., Blackman, C.J., de Dios, V.R., Choat, B., Medlyn, B.E., Li, X., Bradstock, R.A. and Boer, M.M. 2020. Linking forest flammability and plant vulnerability to drought. Forests 11(7), 779.
3. Nolan, R.H., 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. For. Ecol. Manage. 474, 118385.
4. Nolan, R.H., Boer, M.M., Collins, L., Resco de Dios, V., Clarke, H., Jenkins, M., Kenny, B., Bradstock, R.A., 2020. Causes and consequences of eastern Australia's 2019–20 season of mega-fires. Glob. Change Biol. 26, 1039-1041. (Invited Letter).
5. Boer, M. M., Resco de Dios, V. and Bradstock, B.A. 2020. Unprecedented burn area of Australian mega forest fires. Nature Climate Change 10, 171–172.
6. Nolan, R.H., Hedo, J., Arteaga, C., Sugai, T., Resco de Dios, V., 2018. Physiological drought responses improve predictions of live fuel moisture dynamics in a Mediterranean forest. Agricultural and Forest Meteorology 263, 417-427.

Other peer-reviewed research papers with WP2 members on WP2- and Hub-related topics

- Nimmo, D. G., Andersen, A. N., Archibald, S., Boer, M. M., Brotons, L., Parr, C. L., & Tingley, M. W. 2022. Fire ecology for the 21st century: Conserving biodiversity in the age of megafire. Diversity and Distributions 28(3), 350-356.

7. Le Breton, T.D., Lyons, M.B., Nolan, R.H., Penman, T., Williamson, G.J. and Ooi, M.K., 2022. Megafire-induced interval squeeze threatens vegetation at landscape scales. Frontiers in Ecology and the Environment 20(5), pp.327-334.

- Víctor Resco de Dios, Àngel Cunill Camprubí, Núria Pérez-Zanón, Juan Carlos Peña, Edurne Martínez del Castillo, Marcos Rodrigues, Yao Yinan, Marta Yebra, Cristina Vega-García, Matthias M. Boer. 2022. Convergence in critical fuel moisture and fire weather thresholds associated with fire activity in the pyroregions of Mediterranean Europe. Science of the Total Environment 806, 151462.

- Resco De Dios, V., Hedo, J., Cunill Camprubí, A., Thapa, P., Martínez del Castillo, E., Martínez de Aragón,J., Bonet, J.A., Balaguer-Romano, R., Díaz-Sierra, R., Yebra, M. and Boer, M.M. 2021. Climate change induced declines in fuel moisture may turn currently fire-free Pyrenean mountain forests into fire-prone ecosystems. Science of the Total Environment 797, 149104.

8. Collins, L., Bradstock, R.A., Clarke, H., Clarke, M.F., Nolan, R.H. and Penman, T.D., 2021. The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity fire. Environmental Research Letters 16(4), p.044029.

- Martin, M.A., Sendra, O.A., Bastos, A., Bauer, N., Bertram, C., Blenckner, T., Bowen, K., Brando, P.M., Rudolph, T.B., Büchs, M., Bustamante, M., Chen, D., Cleugh, H.,

Dasgupta, P., Denton, F., Donges, J.F., Donkor, F.K., Duan, H., Duarte, C.M., Ebi, K.L., Edwards, C.M., Engel, A., Fisher, E., Fuss, S., Gaertner, J., Gettelman, A., Girardin, C.A.J., Golledge, N.R., Green, J.F., Grose, M.R., Hashizume, M., Hebden, S., Hepach, H., Hirota, M., Hsu, H.-H., Kojima, S., Lele, S., Lorek, S., Lotze, H.K., Matthews, H.D., McCauley, D., Mebratu, D., Mengis, N., Nolan, R.H., Pihl, E., Rahmstorf, S., Redman, A., Reid, C.E., Rockström, J., Rogelj, J., Saunois, M., Sayer, L., Schlosser, P., Sioen, G.B., Spangenberg, J.H., Stammer, D., Sterner, T.N.S., Stevens, N., Thonicke, K., Tian, H., Winkelmann, R. and Woodcock, J. 2021. Ten new insights in climate science 2021 – a horizon scan. Global Sustainability 4 (e25), 1-39.

- Wang, B., Spessa, A., Feng, P., Hou, X., Yue, C., Luo, J.-J., Ciais, P., Waters, C., Cowie, A., Nolan, R.H., Nikonovas, T., Jin, H., Walshaw, H., Wei, J., Guo, X., Liu, D.L. and Yu, Q. 2021. Extreme fire weather is the major driver of severe bushfires in southeast Australia. Science Bulletin 67(6), 655-664.

9. Abram, N.J., Henley, B.J., Sen Gupta, A., Lippmann, T.J., Clarke, H., Dowdy, A.J., Sharples, J.J., Nolan, R.H., Zhang, T., Wooster, M.J. and Wurtzel, J.B. 2021. Connections of climate change and variability to large and extreme forest fires in southeast Australia. Communications Earth and Environment 2(1), 8.

- Bradstock, R.A., Nolan, R.H., Collins, L., Resco de Dios, V., Clarke, H., Jenkins, M., Kenny, B., Boer, M.M., 2020. A broader perspective on the causes and consequences of eastern Australia's 2019–20 season of mega-fires: A response to Adams et al. Glob. Change Biol. 26, e8-e9.

Conference Presentations

- Griebel, A., Boer, M.M., Gordon, C.E., Blackman, C., Choat, B., Ellsworth, D., Madden, P., Medlyn, B., Wujeska-Klause, A., Yebra, M., Younes Cardenas, N. and Nolan, R. International Association of Wildland Fire: Fire and Climate, 2022. Poster presentation: The temporal variability of plant traits during drought strongly determines the moisture content of living canopy fuels.

- Bradstock, R., Nolan, R. H. Ecological Society of Australia 2021, Invited plenary: The 2019/20 mega-fires What did we learn and will it equip us for the future?

- Nolan, R., Collins, L., Gibson, R., Samson, S., Medlyn, B., Price, O., Choat, B. and Boer, M. 9th International Fire Ecology and Management Congress 2021, Post-fire Recovery of Trees and Carbon Stocks One Year After Australia's 2019-20 Black Summer fires.

- Griebel A., Nolan R., Yebra M., Medlyn B., Choat B., Renzullo, L., van Dijk A., Resco de Dios V. and Boer M. NPWS Annual Fire Managers Forum 2021. Work Package 2 (ARC-Linkage): Forecasting live fuel moisture content.
- Boer, Matthias. FireLinks COST-Action, 2021 (Invited). Australia's Black Summer forest fires of 2019/20: a global long-term perspective.

Work Package 3: Greenhouse Gasses and Air Quality

Research team

The chief investigator was Associate Professor Owen Price and the lead researcher was Dr Michael Storey, both from the University of Wollongong. The low cost monitors were build by Hugh Forehead and his team from the UoW SMART Lab. A project analysing previously collected urban air chemistry was conducted by Professor Clare Murphy and Dr Max Desservetaz at UoW. Field and analysis assistance was provided by Steph Samson and other assistance was provided by Michael Bedward, Simin Rahmini and a large team of volunteers including fire agency staff. Members of the advisory group provided useful advice, particularly Lisa Chaing and Ningbo Jiang. Staff from the NPWS fire assisted with selection of sites and support in the field, especially David Croft, Damien Debrowin and Glenn Meade.

Overview

The overarching aim of this work package was to understand whether increasing the amount of prescribed burning would increase or decrease the overall exposure of the NSW population. The problem was broken into a series of connected project to understand the production of smoke in fires, the dispersal of that smoke and how this affected air quality in the mostly urban air-quality monitors operated by the NSW government. First, we measured fuel consumption in 20 prescribed burns (17 Hazard Reduction Burns and three Cultural Burns). We used an array of low-cost particulate monitors around 18 prescribed burns to determine smoke concentrations in the broader landscape during and after the fire. We conducted a series of big-data analyses to measure the effects of individual prescribed burns and collections of burns on air quality in Sydney and the weather patterns associated with poor air quality.

We found that it was not the type of fire that had the biggest impact on $PM_{2.5}$ in Sydney but the *size* of the fire. Typical HRBs produce less smoke that bushfires per hectare and Cultural burns less again. In most cases, the smoke from HRBs affects communities up to 2 km away during the day and 5 km during the following night, but occasionally, the smoke goes 20km or more. Light winds during the fire and the following evening increases the impact both locally and more broadly. Larger fires produce less $PM_{2.5}$ per hectare when measured in Sydney. One analysis showed that whether a fire was a prescribed burn or a wildfire did not affect the amount of smoke that reached Sydney per hectare, but large fires produce relatively less $PM_{2.5}$ per hectare than small fires.

This is thought to be for three reasons: (1) The power of fires increases with size, so that a larger fire produces a plume rising above the land surface; (2) Large fires often occur in wind conditions that blow smoke away from Sydney, such as easterlies that move smoke inland, or strong westerlies blowing smoke directly to sea; (3) HRBs are usually conducted in low wind for safety reasons, but wildfires are more likely to occur in windy weather. Though these conditions drive a bushfire, they also have the effect of blowing smoke through Sydney and out to sea.

Researchers concluded that increasing prescribed burning would increase the population's total exposure to landscape fire-generated particulates.

Aims

To answer the following questions:

1. To what extent does planned burning in NSW add to (or diminish) the total emissions of greenhouse gases?

2. To what extent does planned burning change the overall air quality impacts from vegetation fires?
3. Which planned burning strategies are most likely to reduce GHG emissions

Projects and outcomes

Work Package 3 of the NSW Bushfire Risk Management Research Hub (which ended in 2022) completed research around balancing bushfire risk reduction benefits of prescribed burning with the impacts of smoke on the environment and human health. The output from Work Package 3 is best understood by reviewing the published works (journal articles, other reports). Here, we provide a brief introduction that maps out the aims of Work Package 3. We then summarise each project under Work Package 3 by providing plain language summaries, the abstract and a selected plot/s from the published articles or final reports. We also provide a conclusion in section 3, which is a summary of the findings from Work Package 3 as a whole. We provide the references for the main published documents with the individual project summaries (section 4).

Prescribed burning (a.k.a planned burning, hazard reduction burning) reduces emissions from future bushfires but it creates emissions of its own including greenhouse gases (GHGs) and particulates.

The fundamental challenge is to define prescribed burning strategies that result in:

1. an overall reduction in GHGs, and
2. an overall reduction in human exposure to particulates.

There is a trade-off between emissions from prescribed burning and bushfires. To understand the trade-off, we must estimate the emissions and exposure of pollutants from individual fires of each type and from regional management strategies. The information required to understand exposure to a pollutant from any particular fire is illustrated in Figure 3.1. We must know how much fuel got consumed, how much got turned into the pollutant and where that pollutant is dispersed, in relation to where people live. For greenhouse gas emissions the process is the same, but the final consideration of dispersal is not needed. Defining optimum prescribed burn programs requires integrating this equation for all the fires in a management scenario: all the prescribed burns that are done and the bushfires that are anticipated to occur.

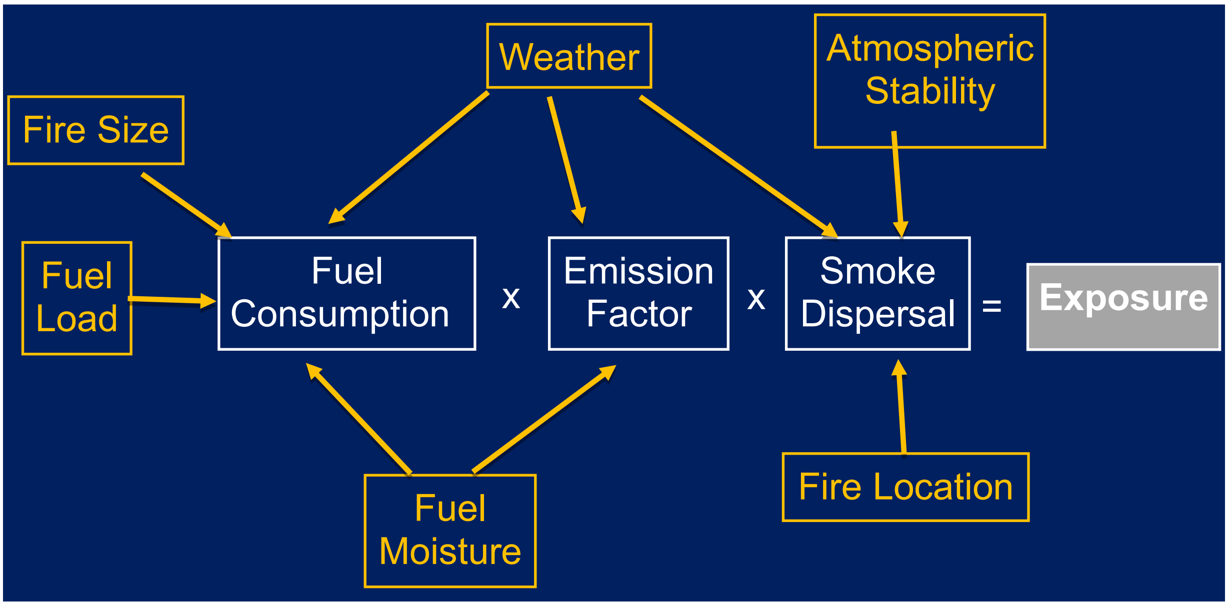


Figure 3.6: The components required to measure exposure and the factors that influence each component.

Each of the projects in Work Package 3 was intended to address one or other of these components. The sections below summarise the projects completed under Work Package 3.

Plain language summaries

Below are plain language summaries of each project from Work Package 3. They are organised as a main "question" and the "answer" from the research, although the main report/article should be read for a full understanding of each project. The abstract for each report or journal article and a figure is included further along in this document (section 4). Each project contributed a new understanding towards the ultimate aim of calculating exposure (of populations, people) from smoke from landscape fires, which is distilled in Figure 3.1. The projects are ordered by broad focus area (fuel first) and the name for each project here is the published journal article or report. Some are not published, which is indicated below.

(Project 3.1.1). Desservettaz, M, Phillips, F, 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

Factors/components: Population exposure to smoke pollution

Question: What pollutants are present in the air in a western Sydney suburbs and what is the contribution of wood-heaters and hazard reduction burns?

Answer: Both sources caused increases of 2-3 fold in the concentration of a range of pollutants compared to ambient conditions. 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.

(Project 4.1) Price, O.F., 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

Factors/components: Fuel consumption

Question: How do fuel consumption rates in dry sclerophyll forests of the Sydney region change depending on the type and intensity of fire?

Answer: How much fuel burnt depended largely on how much fuel was there before the fire (more fuel = more fuel burnt), but also on the severity of the fire (higher severity = more fuel burnt). The type of fire was less important (prescribed fire or wildfire), but more of the larger woody and tree canopy fuels were burnt in wildfires. Measurements from this project can be used to predict how much of each type of fuel would burn (litter, shrubs, canopy, wood) during different types of fire.

(Project 4.2) Reisen, F. Emission factors and fuel moisture. Unpublished work

Factors/components: Fuel moisture, emission factors

Question: How do emission factors from fuels change depending on the fuel moisture level?

Answer: Unpublished data indicate that moist eucalypt leaf litter produces smoke with higher particulate concentrations than does dry eucalypt leaf litter, even though they burn at a similar rate. Mallee eucalypt litter showed a similar effect but litter from Banksia fuel showed the opposite effect.

Note: This work will be written up as part of the research plan in the new Bushfire and Natural Hazards Research Centre.

(Project 4.3) O.F. Price (2020). Evaluation of the RFS Smoke Prediction System. A report to the Rural Fire Service

Factors/components: Smoke dispersal

Question: How accurate is an existing system for predicting smoke dispersal from prescribed burns?

Answer: The existing system is reasonably accurate at predicting the general area of smoke but it is poor at predicting pollution levels ($PM_{2.5}$) that were measured at air quality monitoring stations. Part of the problem is that inaccuracies in the underlying weather predictions (e.g. wind direction predictions) feed through and contribute to errors in the smoke predictions. Predictions were particularly poor during still and stable weather.

(Project 4.4) Simple smoke prediction tool (cylinder). A chapter from Evaluation of the RFS Smoke Prediction System

Factors/components: Smoke dispersal

This presents a simple tool to predict the area (a circle around a fire location) that may be impacted by smoke depending on how big the fire is and what the planetary boundary layer height is. This tool provides general guidance on the possible smoke impact.

(Project 4.5) Price, O.F., Forehead, H., 2021. Smoke patterns around prescribed fires in Australian eucalypt forests, as measured by low-cost particulate monitors. Atmosphere 12, 1389. https://doi.org/10.3390/atmos12111389

Factors/components: Weather, Fire Size, Smoke Dispersal, Exposure

Question: How do pollution levels near prescribed fires vary depending on weather and fire factors?

Answer: Pollution was worst close to the prescribed fire and at bigger fires. During the daytime, pollution could be high up to 2km downwind from a prescribed fire but further at night and also upwind at night, when winds were slower. Conditions that are generally good for doing prescribed burns, particularly cool and still conditions, were worse for smoke pollution. Pollution levels were also worse when there was atmospheric instability and for fires that burnt into the night.

(Project 4.6) Smoke in the 2019-20 bushfires: Distance v PM2.5 and role of low-cost sensors. Unpublished work

Factors/components: Weather, Fire Size, Smoke Dispersal, Exposure

It was intended to conduct smoke sampling from wildfires using low-cost monitors to complement sampling from prescribed burns (Project 4.5). While 4500 hours of data were collected during the 2019/20 bushfires (about 80% of that for Project 4.5), most of the monitors were more than 20 km from the fire front. Preliminary analysis found that this was not sufficient to develop a profile of emissions, even when additional data was sourced from the NSW and ACT government Air Quality networks (including Dustwatch) and private monitors (Purple Air network). Thus, this project was abandoned.

(Project 4.7) Storey, M.A., Price, O.F., 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

Factors/components: Weather, Fire Size, Smoke Dispersal

Question: How do weather and fire factors affect how smoke pollution ($PM_{2.5}$) from individual fires disperses?

Answer: Bigger fires generally more pollution (higher $PM_{2.5}$) from smoke and areas close to the fire had more pollution (particularly within about 20 km). The effects of weather were more complex and depended on the time of day and location relative to the fire. Both high and low levels of several variables were related to high pollution levels. For example, very high or very low wind speeds at the fire (i.e. where smoke was produced) were associated with high pollution levels. At the monitors (i.e. where smoke was observed), low wind speeds were mainly associated with high pollution levels. There may be effects of both calm conditions (low wind, low boundary layer) causing any existing smoke to linger in the area, leading to high pollution levels, but also high fire danger conditions (high wind speed, unstable atmosphere) meaning more intense fires producing more smoke and pollution.

(Project 4.8) Storey, M.A., Price, O.F., 2022. Prediction of air quality in Sydney, Australia as a function of forest fire load and weather using Bayesian statistics. PLOS ONE 17, e0272774. https://doi.org/10.1371/journal.pone.0272774

Factors/components: Weather, Fire Size, Smoke Dispersal

Question: How do regional weather and fire variables affect fire-related pollution ($PM_{2.5}$) in Sydney?

Answer: Worse pollution (higher $PM_{2.5}$) was predicted when there was high pollution the previous day and when fires were bigger, particularly when those fires were to the west and north of Sydney. Worse pollution occurred in Sydney when the wind was blowing smoke from inland and it was trapped or held up by a sea breeze along the Sydney coast. The model in this project can predict the percent chance that pollution ($PM_{2.5}$) will be over a certain level in Sydney.

(Project 4.9) Storey et al (in review) Regional wind patterns associated with poor air quality from forest fires near Sydney, Australia

Factors/components: Weather, Smoke Dispersal

Question: What region-wide wind patterns lead to the worst pollution ($PM_{2.5}$) in Sydney when fires are burning?

Answer: Although many different wind patterns could have high pollution levels, for prescribed fire days, the worst pollution in Sydney was on days with westerly winds over the Blue Mountains and inland, and an opposing sea breeze along the coast. There was a similar result for wildfires but there was more variation in the wind patterns that produced high levels of pollution, particularly during the 2019-2020 fires. For example, some days with very strong westerlies across the region (no sea breeze) had high fire activity and smoke production which resulted in high pollution levels directly under the fire's smoke plume.

(Project 4.10) Price, O.F., Rahmani, S., Samson, S., 2023. Particulate Levels Underneath Landscape Fire Smoke Plumes in the Sydney Region of Australia. Fire 6, 86. https://doi.org/10.3390/fire6030086

Factors/components: Weather, Atmospheric Stability, Fire Size

Question: How often do smoke plumes, that can be seen in satellite imagery, cause high pollution ($PM_{2.5}$) levels at ground level and what influences this?

Answer: Plumes from both wildfires and prescribed fires usually stay aloft, so don't increase pollution ($PM_{2.5}$) at ground level. However, the wind speed, temperature and mixing height all affected the chance of a plume dropping to the surface level and causing high pollution. The chance of high pollution from prescribed burn smoke being detected at ground level increased dramatically when wind speeds were very low. Only 4% of observable prescribed burn plumes passed over an air quality monitor, so most pollution goes undetected.

(Project 4.11) 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, e608–e619. https://doi.org/10.1016/s2542-5196(21)00198-4

Factors/components: Exposure

Question: What are the relative health costs of prescribed burn smoke and wildfire smoke?

Answer: Overall, wildfires had a higher total health cost compared to prescribed burns: between 2000 and 2020, 82% of forest-fire smoke-related health costs were from wildfires. However, on a per-hectare basis, prescribed burns had a higher health cost. The results suggest that from a wildfire and prescribed burn of the same size, the smoke from the prescribed burn would have a greater impact on people's health.

(Project 4.12) Storey and Price (2023), Comparing the effects of wildfire and hazard reduction burning area on air quality in Sydney. Atmosphere 14 (11), 1657

Factors/components: Exposure, summary, trade-off

Question: What are the relative effects of prescribed burn smoke and wildfire smoke on pollution in Sydney?

Answer: The type of fire wasn't important in predicting pollution levels in Sydney, prescribed burns and wildfires had similar effects per hectare. However, small fires had a greater per-hectare effect than very large fires. The results suggest that burning many separate prescribed fires on different days would result in worse air quality in Sydney than burning one large fire on a single day. It was also found that increasing the amount of prescribed burning in the region would likely increase the overall days of poorer air quality, despite a decrease in wildfires due to the preventative effect of the prescribed burns.

Conclusions

The projects forming Work Package 3 of the Hub make a substantial step forward in our understanding of risks from smoke and how to manage those risks. We have integrated our results with historical and contemporary research into a table that summarises how each of the known risk factors (determinants, the rows in Table 1) affect smoke emissions, dispersal and exposure (the columns in Table 1). The determinants are fire intensity, fire area (or size), distance from the fire to the exposure site, fuel dryness, wind speed and atmospheric instability (buoyancy of the air). The table is explained in more detail in the publication for Project 4.12.

Fuel consumption increases with fire size and intensity. Intensity increases with fuel dryness, wind speed, and atmospheric instability (buoyant air). So, the first column in Table 1 shows positive effects for most of the determinants on total fuel consumption. Fuel dryness and fire intensity also decrease emission factors (the fuels burn more completely). This works to counter their positive effects on fuel consumption.

The proportion of the smoke that stays at the surface (third column) is negatively influenced by fire size, intensity and fuel dryness because all of these increase the total energy of the fire, which causes more lofting. Stronger wind encourages burning but lighter winds are associated with night-time temperature inversions trapping smoke near the ground and these two countervailing effects mean wind speed can have both positive and negative effects on smoke near the surface. Transport of the smoke plume over the area where people live (fourth column) depends entirely on weather (wind speed, direction, buoyancy). The four columns are combined into exposure (fifth column), which shows that the fire area has a positive effect on exposure and distance has a negative effect. The other determinants have either positive and negative or unknown effects ("?" in the table), reflecting the fact they have countervailing components, the net effect of which depends on the particular circumstances of the fire and is very hard to predict. These question marks are areas where further research is needed.

Lastly, it should be noted that one project (4.11) found that prescribed burns seem to result in higher exposure than wildfires when considered on a per-hectare basis, while another (4.12) found that per-hectare effects on $PM_{2.5}$ were similar for wildfires and prescribed burns. However, 4.12 found that small fires had a larger per-hectare effect on $PM_{2.5}$ than large fires, and thus a strategy of increasing prescribed burn area (i.e. increasing the number of small fires in the region) may lead to higher overall exposure despite the prescribed burns reducing wildfire area. Important factors influencing these results may include that prescribed burns tend to occur closer to populated areas, under lighter winds that allow smoke to linger and are smaller and less intense, so do not loft smoke as high into the atmosphere.

Table 1: Components of ($PM_{2.5}$) exposure and their potential determinants that have been identified in previous research. Symbols indicate whether, based on previous research, we conclude that the determinant has a positive (+), negative (-), none (.) or unknown (?) effect

on a component of exposure. +- means that positive or negative relationships are possible. Some indirect effects may not be captured here. We have defined the determinants in such a way that all are on average higher in wildfires than prescribed burns.

	Components of Exposure				
	Smoke production		PM transport		PM observed
Determinants	Total fuel consumption	PM emission factors	Proportion of smoke transported near surface	Likelihood of transport over receiver	Surface PM concentration at receiver
Fire intensity	+	-	-	.	?
Fire area	+	.	-	.	+
Distance from fire	.	.	.	-	-
Fuel dryness	+	-	-	.	?
Wind speed	+	-	+-	+	+-
Instability	+	?	-	+	?

This body of evidence suggests that increasing the amount of prescribed burning will increase overall smoke exposure, even though exposure from wildfires is reduced. It also suggests that it is better to conduct large burns rather than split them into smaller chunks. The research points to clear risk factors about weather conditions that make prescribed burning pollution worse. Predominantly this is with stable air and light winds, particularly from the west and when opposed by a sea breeze. However, in practice, it may be hard to avoid these conditions since they are among the safest for conducting prescribed burns.

Key Outputs

Price, O.F., 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

This study was a core component of Work Package 3, i.e. “Fuel consumption” in Figure 3.1 in the introduction.

ABSTRACT: Accurate estimation of emissions from biomass burning and their impact on carbon storage requires field 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

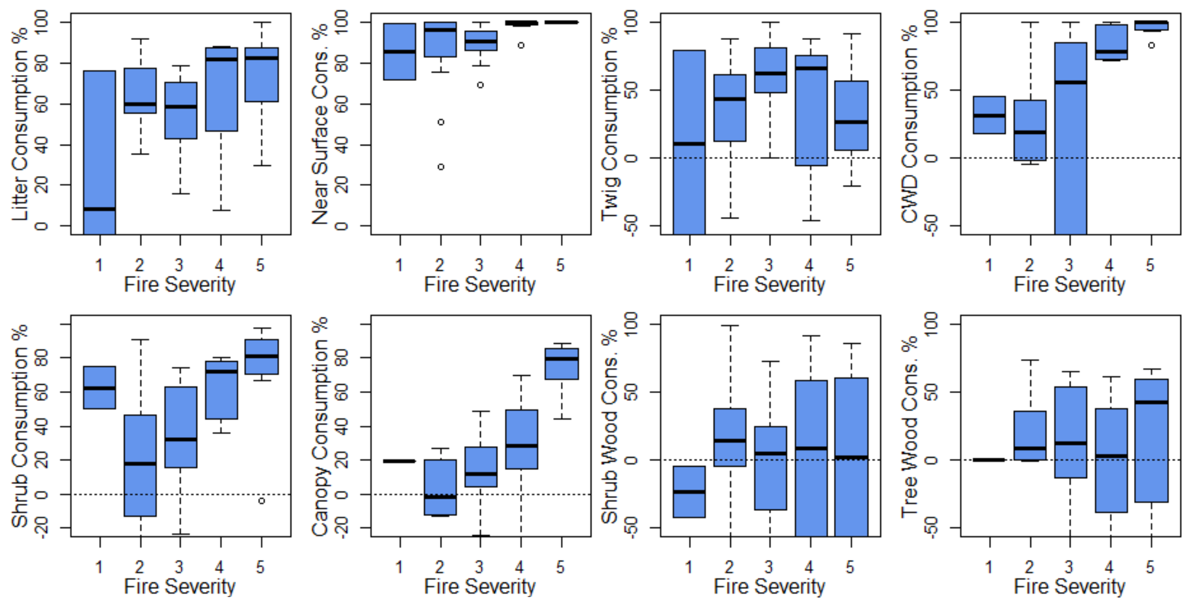


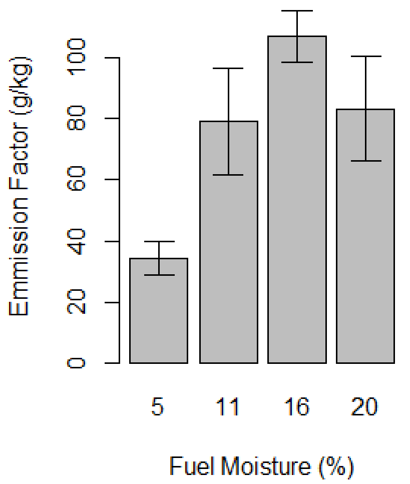
Figure 3.7 Boxplots of fuel consumption for each component against field fire severity expressed as a percentage of pre-fire levels

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 wildfires than in 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.

Reisen, F. Emission factors and fuel moisture. Unpublished work.

The original work package plan included the conduct of an experiment to determine whether the conditions in which HRs occur produce more or less emissions per kg of fuel consumed than bushfires, focussing chiefly on fuel moisture because this is thought to be a factor and HRs and bushfires tend to burn at different moisture contents (project WP3.1.3.1). This became difficult for several reasons, chiefly delays in building the burn facility at UTAS. However, Fabienne Reisen from CSIRO did such an experiment in 2008 but has not written it up. She has kindly given us the data with the intention that we will write a joint paper. She burnt 14 eucalypt litter beds at 4 fuel moisture levels in a 50 x 50 cm fuel bed with sophisticated emission sensors. She found that emission factors for particles in more moist fuels were more than double those in the dryer ones, even though the combustion efficiency (percentage of the fuel consumed) was constant at ~85% (Figure 3). Mallee eucalypt litter showed a similar, but less pronounced trend and Banksia litter showed the opposite trend (lower emission factors in more moist fuel). We can combine these results with our fuel consumption estimates (section 3) to estimate total particulate emissions per hectare. However, this would require data confirming the distribution of fuel moisture content for HR and bushfires, which we do not have.

Figure 3 8: Particulate emission factors for eucalypt fuel beds burnt at different moisture content (data courtesy F. Reisen, CSIRO).



O.F. Price (2020). Evaluation of the RFS Smoke Prediction System. A report to the NSW Rural Fire Service

To evaluate the smoke prediction model, we compared the hourly $PM_{2.5}$ predictions from 74 model runs against the observed $PM_{2.5}$ values at 21 reference monitors operated by DPIE (a total of 49,000 observations). This work was project WP3.2.4 in the Hub plan, and the results were provided in a report to the RFS: Price, O (2020) Evaluation of the RFS Smoke Prediction System (Draft). NSW Bushfire Risk Research Hub.

- While the model was reasonable at predicting the general spatial pattern of smoke dispersion, it performed poorly at predicting $PM_{2.5}$ observations, on average explaining less than 6% of the observed variation, with a mean error of 13.8 μgm^{-3} and correctly predicting only 1% of hourly $PM_{2.5}$ exceedances.
- Part of the problem is that the underlying weather model introduces error. For example, the mean difference between the predicted and observed wind direction was 40°.
- The predictions were particularly poor during still and stable weather.
- The model also suffers from not including non-smoke sources of pollution.

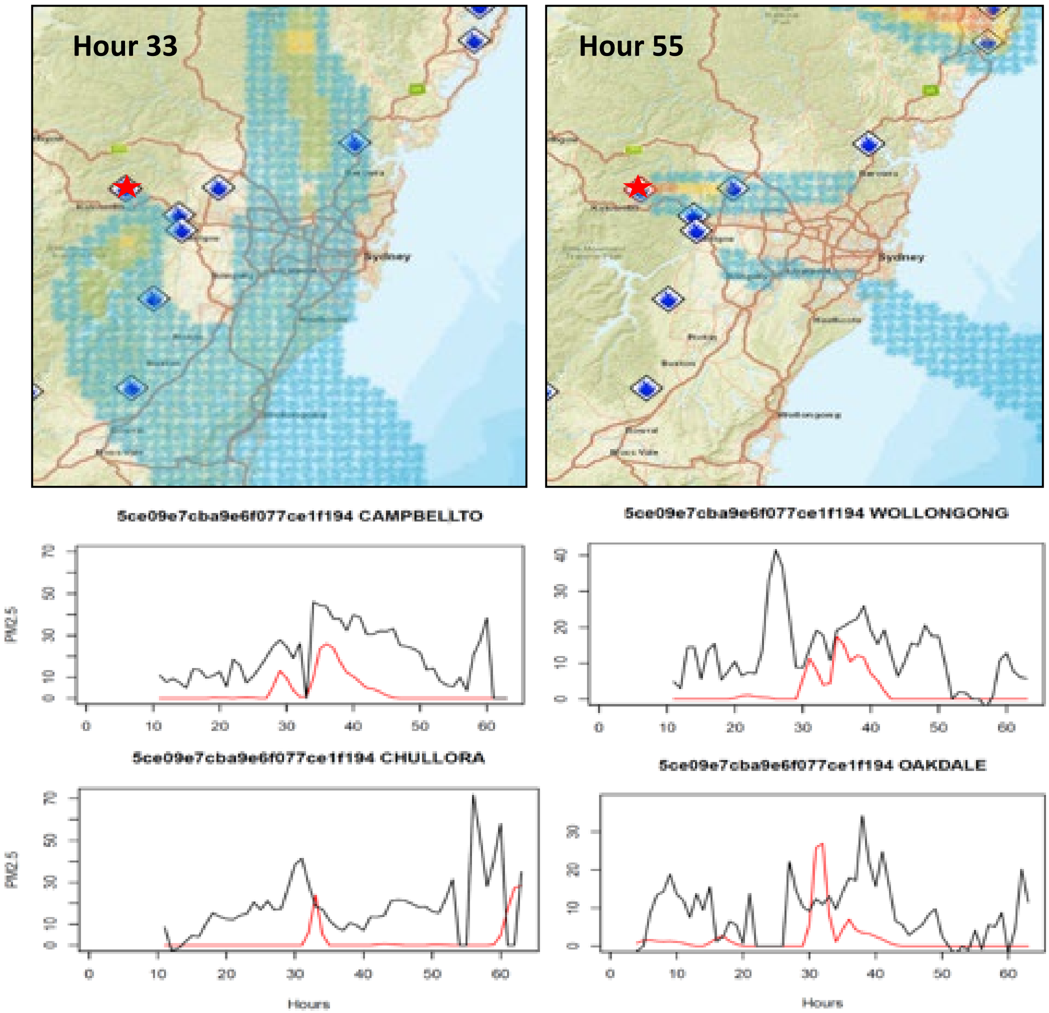


Figure 3.9: An example of the output from one RFS smoke model at two timesteps, and time trace of observed and predicted PM2.5 at four DPIE monitors.

Simple smoke prediction tool (cylinder). Chapter from Evaluation of the RFS Smoke Prediction System (Project 4.3).

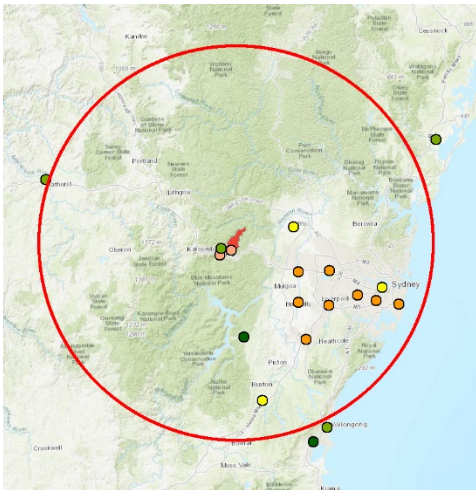


Figure 3.5: The smoke radius model as it appears in the Excel spreadsheet.

A simple model of smoke impact potential is presented that calculates the radius of the circle that could exceed tolerable $PM_{2.5}$ levels as a function of the area of the planned fire and the height of the mixing layer. Applying this model to the Lawson Ridge fire suggested it had the potential to affect all areas up to 117 km from its centre. The model also highlights the importance of high pressure systems in the Tasman Sea which limit the dispersal of smoke. Similar weather conditions have caused air pollution events in Sydney from fires in the lower Blue Mountains in at least six different years since 2000.

Smoke Cylinder radius calculator

User Input	**Value**	**Units**	**Notes**
Area to be burnt	3000	ha	
Planetary Boundary Layer Height	700	m	Predicted PBLH for the period of interest (e.g. average over multiple days).
Model Constants			
Current Background AQ	9	μgm^{-3}	Default is 9, mean daily value for Liverpool DPIE AQ monitor, 2000-2019
Fuel consumed per ha	10	$t\ ha^{-1}$	Based on NSW Bushfire Risk Research Hub data
Emission factor (Proportion of $PM_{2.5}$ in emissions)	0.016		Based on Reisen, et al (2018)
Tolerable level particles	25	μgm^{-3}	National Environmental Protection Measure 24-hour standard
Model Predictions			
Total weight of $PM_{2.5}$ emissions	480	t	Fire area * fuel per ha * emission factor
Volume occupied at tolerable level	1.92E+13	m^3	Weight of emissions / tolerable concentration

Volume occupied at tolerable level (smoke plus background)	3E+13	m^3	
Estimated radius (smoke only)	93	km	Radius of circle containing the volume above
Estimated radius (background plus smoke)	**117**	**km**	

Moderators (red flags)		
Is there a high pressure system in the Tasman sea?	Yes/No	If yes, impact is much more likely
No southerly wind change forecast for at least 48 hours?	Yes/No	If yes, impact is much more likely

Price, O.F., Forehead, H., 2021. Smoke patterns around prescribed fires in Australian eucalypt forests, as measured by low-cost particulate monitors. Atmosphere 12, 1389.
https://doi.org/10.3390/atmos12111389

This project was a core WP3 component: how much and where does smoke disperse from HR burns?

ABSTRACT: 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 sensors. During the day of the burn, $PM_{2.5}$ tended to exceed hourly standard for poor air quality up to 2-7 km from the fire but only in the downwind direction. In the evening this zone expanded to up to 8-20 km and included upwind areas. $PM_{2.5}$ concentrations were higher in still and cool weather. For example with wind speed of 5 km^{-1} and temperature of 10°C, the statistical model predicted that in the evening, poor air quality will extend 20 km. $PM_{2.5}$ concentrations were also higher in larger fires and those burning under higher atmospheric pressure but these effects were weak. Applying the statistical models predicts that prescribed burns of 1000 ha can be expected to cause air quality exceedances over an area of ~100,000 ha. Stable, still, cool weather that reduces risk of fire escape, have the highest potential for polluting nearby communities and fires that burn into the night are particularly bad.

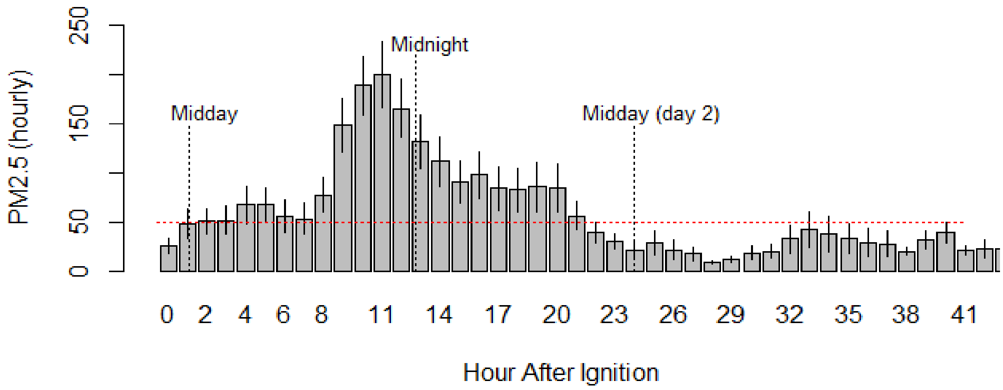
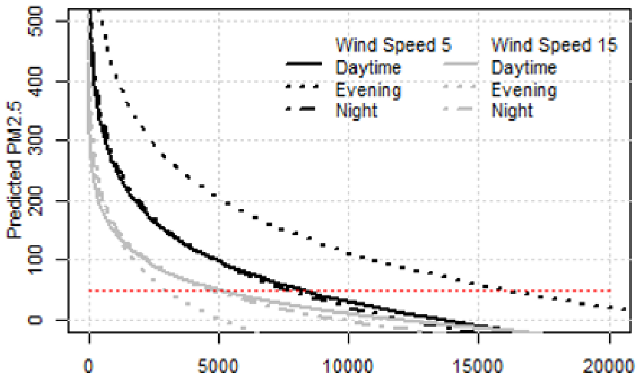


Figure 3.10: Average time-trace for the combined hourly observations (only those > 5km from fires).

Figure 3.11: Model predictions for the analysis of PM2.5 by periods exploring the relationships with distance, wind angle, and wind speed.



Smoke in the 2019-20 bushfires: Distance v $PM_{2.5}$ and role of low-cost sensors. Unpublished work.

Initially, the project had intended to deploy low costs monitors to 30 bushfires in the same way as for HR burns, but this proved impossible due to the danger posed by the huge 2019-20 bushfires. Only 25 such deployments were made and none of these were <10 km from the fires. Instead, we compiled a dataset of 4700 daily observations for active fires days during the 2019-20 season using all of the monitors we could get data from: DPIE reference monitors (68% of observations); our low-cost monitors (8%); DPIE Koalas (7%); DPIE Dustwatch (6%), ACT Government (4%) and Purple Air (2%). Although the reference monitors were the majority of observations, they measured only 49% of the total $PM_{2.5}$, and only 30% of the PM2.5 for observations closer than 50km from the fire source. Only 1.4% of reference monitor observations were closer than 20 km from the active fire, and 3.3% of the other observations were (Figure 8).

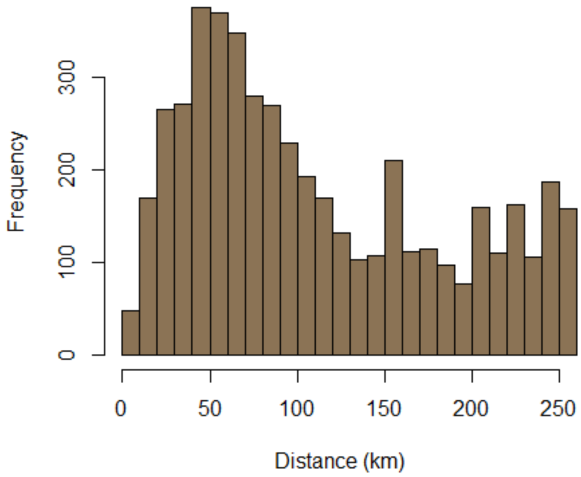
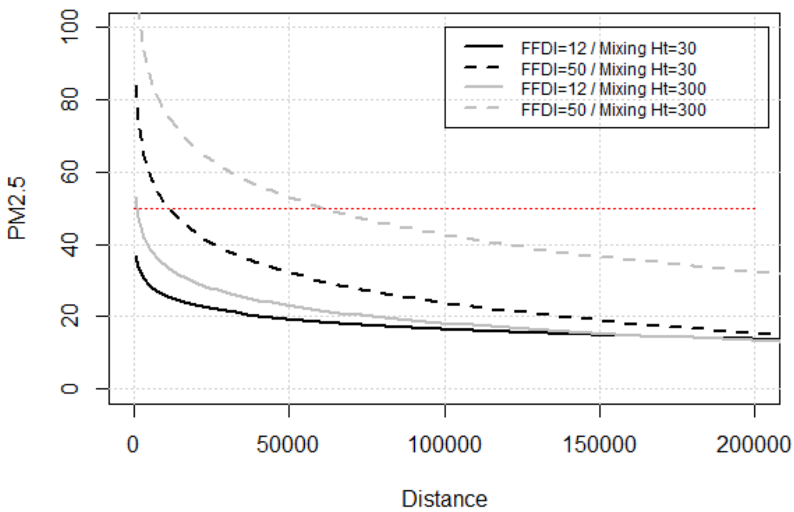


Figure 3.12: Distribution of distances from active fire centres for all combinations of monitor v active fire day July 2019 – June 2020 (distance cut-off 250 km, n = 4700).

Preliminary analysis has been to fit a simple generalised linear model with daytime (10-1700 hrs) $PM_{2.5}$ observations as the dependent variable and (log) distance, wind angle (angle from the straight line between fire and monitor) and weather as predictors. The resultant model indicates a strong distance effect and higher $PM_{2.5}$ under more extreme fire weather and higher mixing height (Figure 9). While the identified effects were strong, the predictive power of the model is weak, explaining only 10% of the variance in $PM_{2.5}$.

Figure 3.13: Preliminary statistical model of PM2.5 during the daytime (7 hour mean) v distance, controlling for fire weather and mixing height



Storey, M.A., Price, O.F., 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

ABSTRACT: Wildfires and hazard reduction burns produce smoke that contains pollutants including particulate matter. Particulate matter less than 2.5 µm in diameter ($PM_{2.5}$) is harmful to human health, potentially causing cardiovascular and respiratory issues that can lead to premature deaths. $PM_{2.5}$ levels depend on environmental conditions, fire behaviour

and smoke dispersal patterns. Fire management agencies need to understand and predict $PM_{2.5}$ 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 $PM_{2.5}$ pollution. We modelled $PM_{2.5}$, 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 $PM_{2.5}$ levels to understand drivers of and predict $PM_{2.5}$. 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 $PM_{2.5}$ with decreasing distance, with a sharp increase when the fire was within 20 km. The models improve our understanding of the drivers of $PM_{2.5}$ from individual fires and demonstrate a promising approach to $PM_{2.5}$ model development. However, although the models predicted well overall, there were several large under-predictions of $PM_{2.5}$ that mean further model development would be required for the models to be deployed operationally.

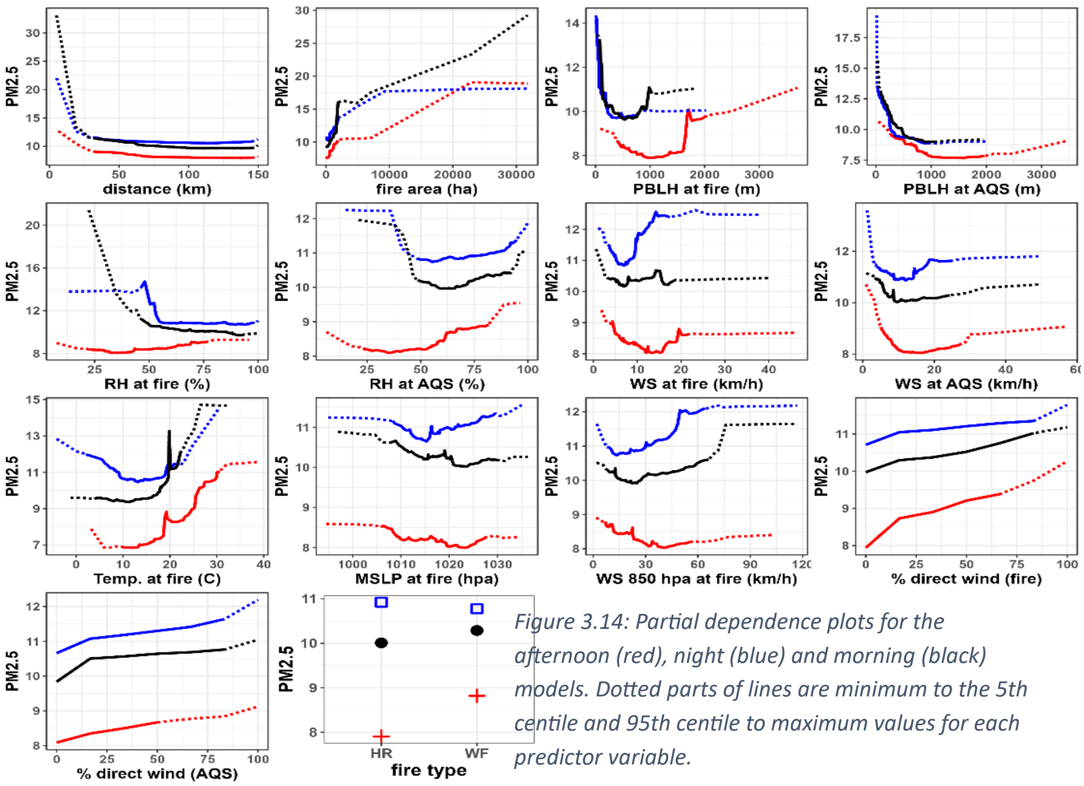


Figure 3.14: Partial dependence plots for the afternoon (red), night (blue) and morning (black) models. Dotted parts of lines are minimum to the 5th centile and 95th centile to maximum values for each predictor variable.

Storey, M.A., Price, O.F., 2022. Prediction of air quality in Sydney, Australia as a function of forest fire load and weather using Bayesian statistics. PLOS ONE 17, e0272774.
https://doi.org/10.1371/journal.pone.0272774

ABSTRACT: 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 ($PM_{2.5}$), which affects human cardiovascular and respiratory systems and can lead to increased hospitalisations and premature deaths. Better models are needed to predict $PM_{2.5}$ 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 $PM_{2.5}$ 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 $PM_{2.5}$, weather reanalysis and satellite fire hotspot data. The models predict that the worst $PM_{2.5}$ in Sydney occurs when $PM_{2.5}$ 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 $PM_{2.5}$ 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 $PM_{2.5}$ models for wildfires.

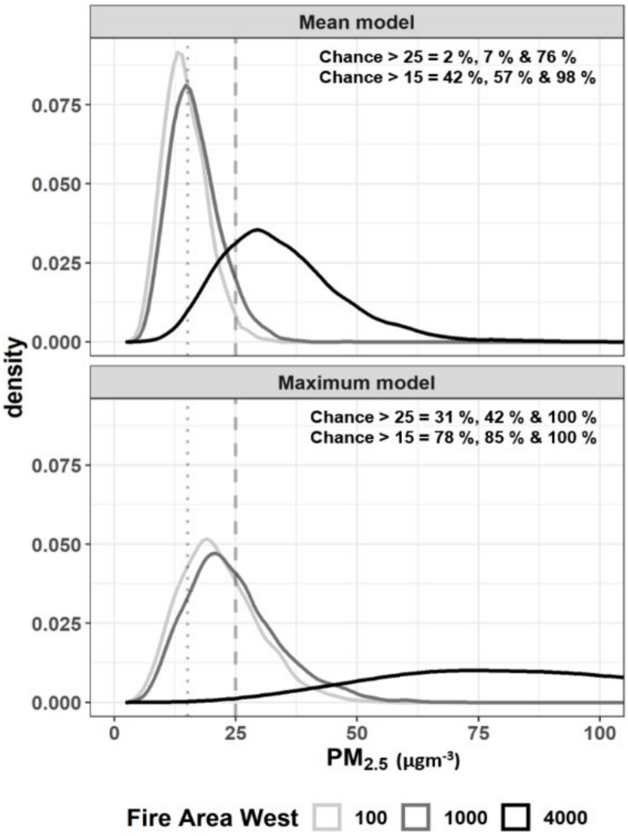


Figure 3.15: Predictive distributions from the mean and maximum daily Sydney PM2.5 models. Predictions for three levels of fire area west, with other variables at set levels: Lag PM2.5=10 μgm-3,ventilation index=500 m2 s−1, temperature=10 C, fire areas south and north=100 ha, coast wind speed and direction=10 km h-1 and easterly (sea breeze), inland wind speed and direction=10 km h-1 and westerly. Dotted and dashed vertical lines are thresholds defined at 15 μgm-3 and 25 μgm-3 respectively, with percent of distribution > thresholds indicated in text within the plots.

Storey, M, Price, OF, Fox-Hughes, P (2023) The influence of regional wind patterns on air quality during forest fires near Sydney, Australia. *Science of the Total Environment* 905, 167335.

ABSTRACT: Smoke from forest fires is a major source of particulate pollution. Particulate pollution threatens the health of communities by increasing the occurrence of respiratory illnesses. Wind is a major driver of fire behaviour and smoke dispersal. It is important to understand wind patterns at a regional scale in order to effectively manage smoke risk. Sydney, Australia is prone to smoke pollution because it has a large population close to fire-prone eucalypt forests.

Here we use the self-organising maps (SOM) technique to identify sixteen unique wind classes in the Sydney region that occurred on days with active fires. We used wind data from 4 pm to help identify sea breeze occurrence. We explored the differences in $PM_{2.5}$ levels between classes and between days classified as either hazard reduction burning (HRB) or wildfire. For HRB days, the classes associated with the highest $PM_{2.5}$ (especially classes 9 and 10) mostly had a sea breeze, whereas better air quality days usually had winds aligned across the region (e.g. all westerly). The wind class with the most hazard reduction burning days had low wind speeds and a sea breeze and was among the worst wind classes for air quality.

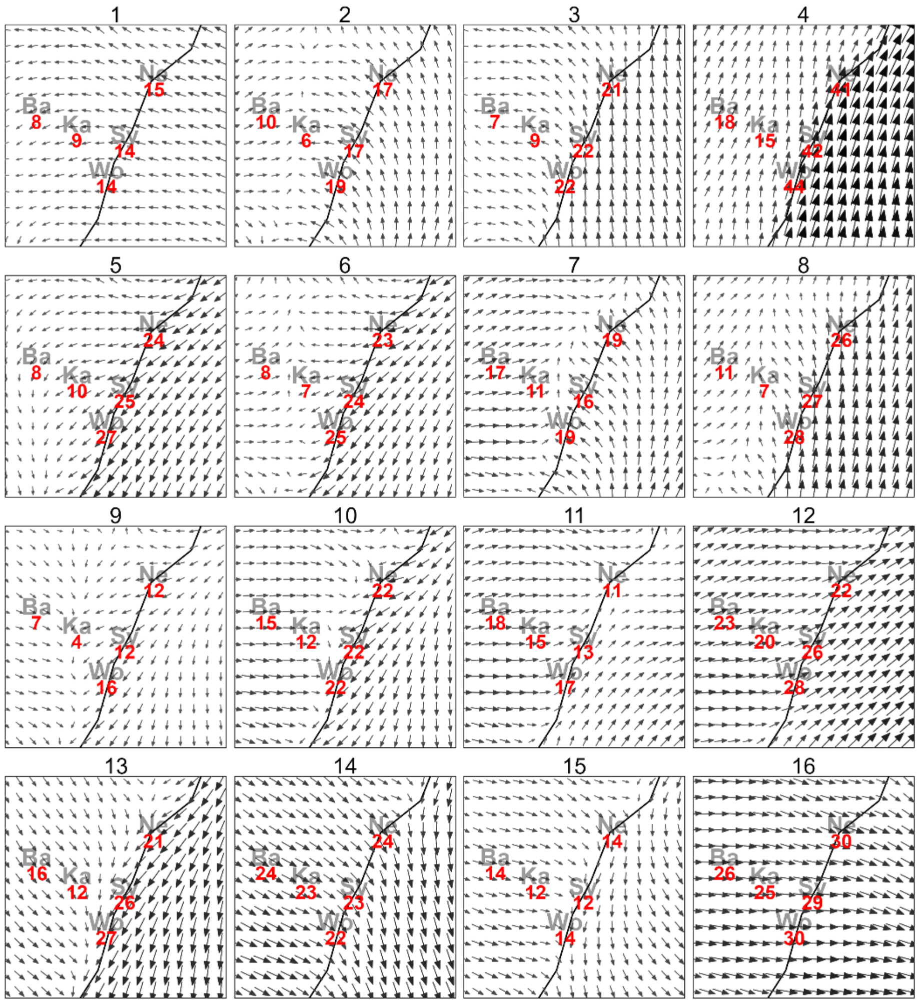


Figure 3.16: Mean wind speed and direction maps arranged on SOM grid. Each arrow is an ERA5 grid cell where mean 16:00 U and V were calculated for each day in each class. The long black line is the coast. Each arrow represents wind direction and speed calculated from the mean U and V: bigger arrows mean faster wind speed. Wind sample locations were: Ba=Bathurst, Ka=Katoomba, Sy=Sydney, Ne=Newcastle, Wo=Wollongong. The mean wind speed per location and class is shown in red (km h-1).

Price, O.F., Rahmani, S., Samson, S., 2023. Particulate Levels Underneath Landscape Fire Smoke Plumes in the Sydney Region of Australia. Fire 6, 86.
https://doi.org/10.3390/fire6030086

ABSTRACT: 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 ($PM_{2.5}$) 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 $PM_{2.5}$: 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 km hr^{-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.

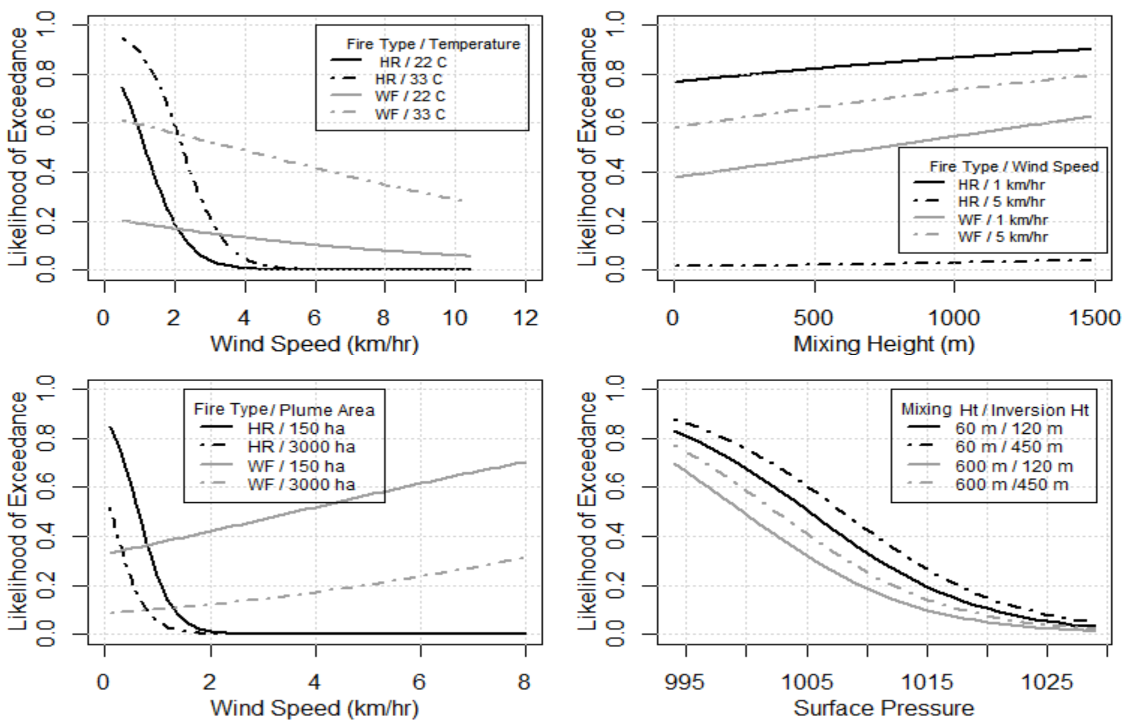


Figure 3.17: Binomial model relationships for (a) daytime and (b) night-time poor air quality exceedances.

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, e608–e619. **https://doi.org/10.1016/s2542-5196(21)00198-4**

This journal article is the published version of Nicolas's **Borchers-Arriagada** PhD chapters

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.

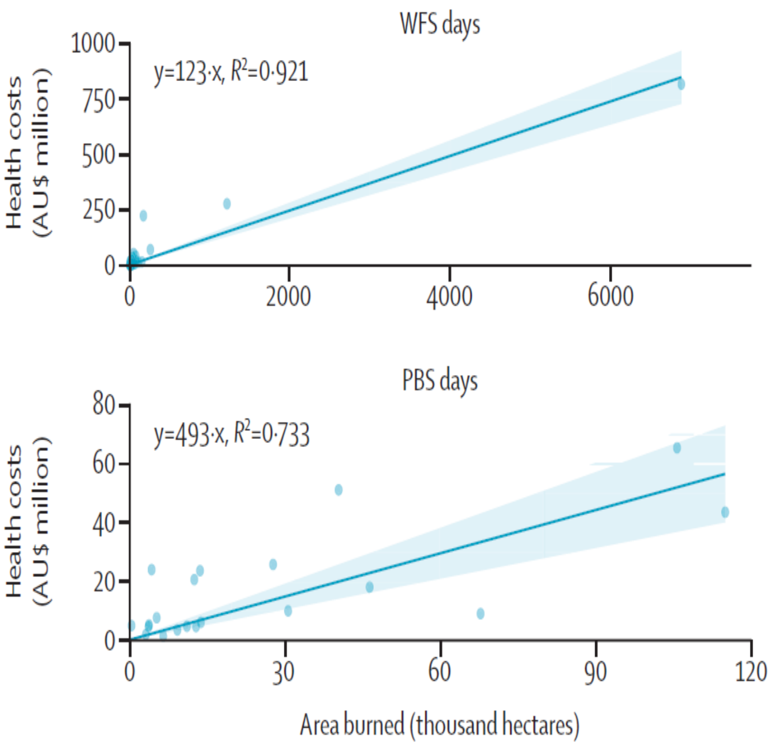


Figure 3.18: Predicted health costs (as a function of population weighted exposure for NSW) for days dominated by Wildfire (WSF days) and by HR (PBS days).

Storey and Price (2023) Comparing the effects of wildfire and hazard reduction burning area on air quality in Sydney. *Atmosphere* 14 (11), 1657.
https://doi.org/10.3390/atmos14111657

ABSTRACT: Landscape fires emit smoke that contains particulate matter (PM) that can be harmful to human health. Prescribed fires or hazard reduction burns (HRBs), ignited under controlled circumstances, and wildfires, uncontained and potentially rapidly spreading fires, can substantially reduce air quality in populated areas. While HRBs reduce the size and PM output of future wildfires, they also produce PM, thus increasing the total PM exposure of populations (prescribed + wildfire PM). There is a critical question of whether conducting HRBs adds to or reduces the total PM exposure of populations. This is important to understand so fire and health agencies can take appropriate actions to ensure community health.

Here we use satellite-based measures of fire area to compare the effect of HRB and wildfire area on 24-hour $PM_{2.5}$ levels in Sydney, Australia. We fitted a generalised linear model with fire type, daily active fire area and weather predictor variables. We fitted the model with an interaction between fire area and fire type to compare the effects of HRB and wildfire area. We then used the model to predict for increased HRB area scenarios and calculated the number of prescribed and wildfire days with $PM_{2.5}$ > 12.5 µgm-3 25 ("Fair" or worse air quality) under each scenario.

HRB area and wildfire area in the Sydney region had similar effects on 24-hour mean $PM_{2.5}$ in Sydney. Increasing HRB area produced substantial increases in HRB exceedance days (> 12.5 µgm-3 27) in Sydney but there was only a small reduction in exceedance days associated with wildfires. Our results indicate that small fires have a higher per-hectare impact on PM levels and increasing HRB area would result in more poor air quality days overall (HRB + wildfire days) in Sydney. We also give context to our work by reviewing recent research on landscape fire and PM exposure.

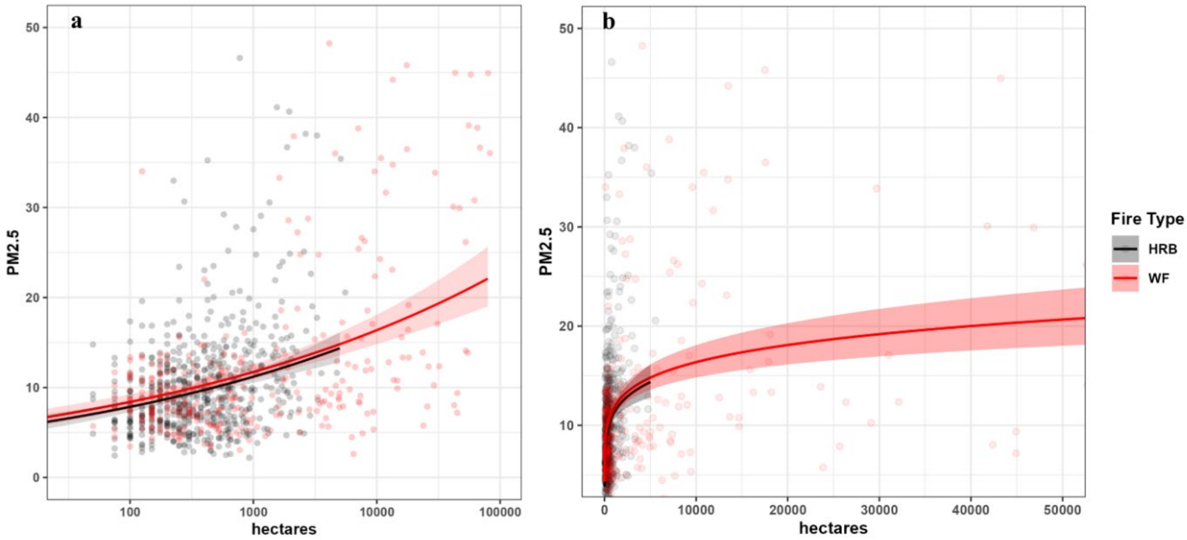


Figure 3.19: Effects plots for fire area (hectares) from the generalised linear model. Fire area (hectares) was log-transformed (base 10) for the model. PM2.5 units are µgm-3. Predictions are within the range of the training data for each fire type. (a) shows the area burnt effect on log10 scale, (b) is back-transformed to natural/original scale, limited to 50000 ha.

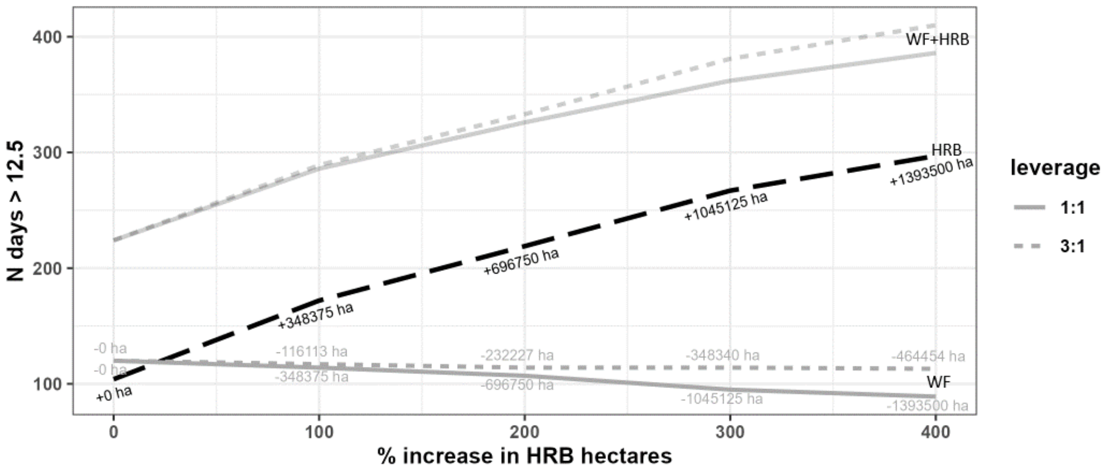


Figure 3.20: Results of trade-off analysis. Plot shows the changes in the predicted number of days > 12.5 µgm-3 from increasing hazard reduction burn (HRB) area from 0 % to 400 % above the actual amount in model data. The number of days and hectare changes are over the whole study period (2012 to 2021). The black long-dash line is HRB days, grey lines at the bottom for wildfires by leverage applied (see legend). Grey lines at the top are the total of WF and HRB days by scenario and leverage. Hectares change under each scenario shown in text near the applicable line.

Full publications list

Borchers-Arriagada, N, Bowman, D, Price, O, Palmer, AJ, Samson, S, Clarke, H, Sepulveda, G, Johnston, FH (2021) Smoke health costs and the calculus for wildfires fuel management: a modelling study. *Lancet Planetary Health* **5**, E608-E619.

Borchers-Arriagada, N, Palmer, AJ, Bowman, D, Williamson, GJ, Johnston, FH (2020) Health Impacts of Ambient Biomass Smoke in Tasmania, Australia. *International Journal of Environmental Research and Public Health* **17**,

Campbell, SL, Jones, PJ, Williamson, GJ, Wheeler, AJ, Lucani, C, Bowman, D, Johnston, FH (2020) Using Digital Technology to Protect Health in Prolonged Poor Air Quality Episodes: A Case Study of the AirRater App during the Australian 2019-20 Fires. *Fire-Switzerland* **3**,

Desservettaz, M, Phillips, F, 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**,

Jones, PJ, Furlaud, JM, Williamson, GJ, Johnston, FH, Bowman, D (2022) Smoke pollution must be part of the savanna fire management equation: A case study from Darwin, Australia. *Ambio* **51**, 2214-2226.

Price, O, Roberts, B (2022) The role of construction standards on building impact of the 2013 Linksview Wildfire, Australia. *Fire Safety Journal* **128**,

Price, OF, Bedward, M (2020) Using a statistical model of past wildfire spread to quantify and map the likelihood of fire reaching assets and prioritise fuel treatments. *International Journal of Wildland Fire* **29**, 401-413.

Price, OF, Forehead, H (2021) Smoke Patterns around Prescribed Fires in Australian Eucalypt Forests, as Measured by Low-Cost Particulate Monitors. *Atmosphere* **12**,

Price, OF, Rahmani, S, Samson, S (2023) Particulate Levels Underneath Landscape Fire Smoke Plumes in the Sydney Region of Australia. *Fire-Switzerland* **6**,

Price, OF, Whittaker, J, Gibbons, P, Bradstock, R (2021) Comprehensive Examination of the Determinants of Damage to Houses in Two Wildfires in Eastern Australia in 2013. *Fire-Switzerland* **4**,

Schumann, RL, Mockrin, M, Syphard, AD, Whittaker, J, Price, O, Gaither, CJ, Emrich, CT, Butsic, V (2020) Wildfire recovery as a "hot moment" for creating fire-adapted communities. *International Journal of Disaster Risk Reduction* **42**,

Simpson, H, Bradstock, R, Price, O (2019) A Temporal Framework of Large Wildfire Suppression in Practice, a Qualitative Descriptive Study. *Forests* **10**,

Simpson, H, Bradstock, R, Price, O (2021) Quantifying the Prevalence and Practice of Suppression Firing with Operational Data from Large Fires in Victoria, Australia. *Fire-Switzerland* **4**, Storey, MA, Bedward, M, Price, OF, Bradstock, RA, Sharples, JJ (2021) Derivation of a Bayesian fire spread model using large-scale wildfire observations. *Environmental Modelling & Software* **144**,

Storey, MA, Price, OF (2022) Prediction of air quality in Sydney, Australia as a function of forest fire load and weather using Bayesian statistics. *Plos One* **17**,

Storey, MA, Price, OF (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.

Storey, MA, Price, OF, Almeida, M, Ribeiro, C, Bradstock, RA, Sharples, JJ (2021) Experiments on the influence of spot fire and topography interaction on fire rate of spread. *Plos One* **16**,

Storey, MA, Price, OF, Bradstock, RA, Sharples, JJ (2020) Analysis of Variation in Distance, Number, and Distribution of Spotting in Southeast Australian Wildfires. *Fire-Switzerland* **3**,

Storey, MA, Price, OF, Sharples, JJ, Bradstock, RA (2020) Drivers of long-distance spotting during wildfires in south-eastern Australia. *International Journal of Wildland Fire* **29**, 459-472.

Work Package 4. Fire regime Thresholds of Potential Concern for threatened biodiversity

Credit: David Keith, Post-fire forest regeneration Maxwells Creek Flora Reserve 2022

Centre for Ecosystem Science   UNSW SYDNEY

Research Team

WP4 Researchers: David Keith, Mark Ooi, Jose Ferrer-Paris, Ada Sanchez-Mercado, Ryan Tangney, Mitch Lyons, Will Cornwell, Dan Falster, Miriam Munoz-Rojas, Nathali Machado de Lima (all UNSW) plus key input from research students Justin Collette, Tom Le Breton, Berin Mackenzie, Ruby Paroissien, Alex Thomsen, Chantelle Doyle (all PhD candidates), Annabel Murray (Masters), and Eleanor Carter, Mirima Goldman, Mira Jordan, Braden Riles, Michi Sano and Sophie Yang (all Honours students). Key collaborators outside UNSW included Tony Auld, Andrew Denham, Berin Mackenzie, Liz Tasker, Andrew Denham and Mark Tozer (all NSW DPIE), Rachael Gallagher (Macquarie/Western Sydney University), as well as Hub researchers Rachael Nolan (WSU), Hamish Clarke, Owen Price, Ross Bradstock (all UOW) and Grant Williamson (UTas).

Overview

Work Package 4 (WP4) focused on two concurrent broad projects; review and reform of plant trait inventory for NSW (Part 1) and the generation of trait data and its response to specific fire regime elements, particularly fire severity and fire season (Part 2). Projects in Part 2 generate data to feed into the inventory developed in Part 1 and provide an understanding of the impacts of shifting fire regimes on at-risk species and communities. These objectives were achieved using field survey data of plant populations for both common and threatened species and provided one of the first assessments of impacts of extreme fire severity and the potential for recovery of an endangered ecological community. In the following we highlight some of the key advances made by WP4 and provide an overview of the key research outputs.

We generated datasets through extensive fieldwork experiments and carried out investigations on selected threatened species, as well as common species that represent a range of fire response types, to characterise their sensitivities to components of the fire regime, emphasising previously neglected effects of season and severity.

Key contributions from WP4 were:

- **A database structure for plant traits** that incorporates spatially and temporally explicit field observations of fire response, developed and delivered to DPIE
- **A web application of the plant trait database** with user-registered open access
- **A field protocol developed by David Keith** that enables trait observations to be linked to a place, time and fire event(s), and enables variability in responses to be captured and related to their causal agents (now taken up by many DPIE survey staff)
- **New post-fire field datasets for forests, heathlands and wetlands** used in developing and testing the traits database operability
- **Post-fire assessments of 135 threatened species and 8 ecological communities** after the 2019-2020 fires
- Contributions as **members of the core team that rapidly assessed priority NSW plant species at risk from 2019-2020** fires (Auld et al. 2022) (Led by Auld, contributions from Keith, Ooi, Le Breton)
- **Submissions to the NSW Inquiry into the 2019-2020 bushfires (requested by DPIE)**
- Input to framework (Gallagher et al. 2022) for rapid post-fire vulnerability assessment of plant species (Led by Gallagher, contributions from Keith, Ooi (WP4), Nolan (WP3)
- **Development of framework (Keith et al. 2022) for rapid post-fire vulnerability assessment of ecological communities**
- **Ecological study of 57 plant species, including 12 threatened species, plus 2 threatened ecological communities**, enabling recommendations for management

- Assessment of dormancy type of 3990 species, feeding NSW species into database
- **Delivered 5 presentations to DPIE managers**, and regular engagement with popular media

Mid-way through our investigations, our research group was asked to pivot to assessing the 2019-2020 Black Summer bushfire season, and subsequently emphasis moved towards extreme fire events and their impacts on biodiversity. While our original aim was to explore the effects of alternative fire regimes on population persistence using population models, the additional work on the Black Summer fires took priority. Nevertheless, estimates of Thresholds of Potential Concern for application in fire management and burning policies were still developed for multiple species.

Additional research funding acquired by WP4

The resourcing required to undertake significant amounts of fieldwork to meet these objectives was obtained by leveraging over $3.4 million funding, at a ratio of ~4:1 on DPE funding to WP4, and directing the work of six PhD and eight Honours students to Hub-focused outcomes. Collaborations between other UNSW researchers also contributed to these outcomes.

Aims

To fill strategic knowledge gaps surrounding fire-related traits to provide data that would provide the foundations for informed fire management for positive ecological outcomes. The basis for this was to quantify responses of key taxa to under-studied elements of the fire regime, data which would both provide this foundation and feed into the database structure developed.

Projects and outcomes

Part 1. Plant Fire Ecology Trait Database

David Keith and Jose Ferrer Paris

While improvement of the existing inventory was a key component of Hub activity under WP4, the Hub was able to leverage prior work initiated under other programs and leverage resources from external sources to support progress towards a more reliable and comprehensive inventory, to support estimation of fire management thresholds for biodiversity conservation. This report places the Hub's work in the context of broader ongoing activities.

Plant life history traits have long been recognised as important for understanding and predicting responses of plant populations to fire regimes (Gill 1975; Noble & Slatyer 1980). A formal inventory of plant life history traits was initiated in 1992, with a list of species assigned to functional groupings based on selected traits (Gill & Bradstock 1992). This inventory was adopted by the National Parks and Wildlife Service as the 'NSW Fire Response Database' (NSWFRDB) to support its fire management program and went through two main phases of update (Bradstock & Kenny 2003; Kenny et al. unpubl. 2014). These updates primarily involved additional sources, increasing the number of species attributed. Minor additions were made to trait fields, but the structure of the inventory (as a stand-alone spreadsheet) remained the same, with a focus on traits originally identified by Gill (1975).

In 2016, a review of the database structure and content was initiated by UNSW, with the aim of upgrading both, setting directions for future collection of data and improving utility of the inventory for management and research applications. Phase 1 of this work began in 2016 as part of Project 1.3 in the NESP Threatened Species Conservation Hub.

Phase 1 included a critical review of existing database structures in the NSWFRDB spreadsheet and development of database design principles. Phase 2, supported by UNSW and the NSW Bushfire Research Hub (Work Package 4), included development of a database design that conformed with principles in Phase 1 in a structure that could be integrated into the NSW BioNet information platform administered by the NSW Department of Planning and Environment. Phase 2 also produced an early prototype database with a core subset of traits using UNSW computing infrastructure with test data sets collected by UNSW staff with support of the Hub and Commonwealth Wildlife and Habitat Recovery Program.

Phase 3, supported by the DCCEW Applied Bushfire Science Program and UNSW, allowed migration of the UNSW prototype to an open-source web application, and important export functionalities were developed, and additional priority traits were added.

Further development is being undertaken, as resources permit, to incorporate additional functionality. They include addition of more of the priority traits identified in consultation with DCCEW staff, and import/migration of additional data sources, particularly those included within the NSWFRDB. The migration highlighted several problems and a need for extensive review and verification of original data sources to ensure a minimum standard of quality assurance. The current version of the database (v1.00) includes 14 plant traits, with a further 24 defined for future development.

Phase 1

Phase 1 of the work included a critical review of existing database structures, identification of key limitations and the development of design principles for a new database to accommodate recent advances in understanding of population- and community-level responses to fire regimes, recognising the diverse resolution and format of data sources. The historical focus on plant taxa was maintained due to the substantial body of research on plant life history processes in relation to fire, the importance of plants in structuring habitats of other species, community assembly and in ecosystem functioning, as well as a substantial body of data available in a wide range of formats and thematic resolutions. We anticipate future extension of the underlying concepts of the plant data base to other taxa.

Review of existing data repository

Phase 1 produced the following conclusions about the NSW Fire Response Database (NSWFRDB):

- Existing plant fire response data bases were founded primarily on a small number of binary or multi-state trait variables and pre-determined functional groups (e.g. Gill 1975; Noble & Slatyer 1980; Gill & Bradstock 1990). A range of plant life history and morphological traits relevant to fire responses were not included.
- The unit of observation was a taxon, with some taxa attributed trait values on the basis of multiple sources.
- Data were stored in spreadsheet format with taxa as rows, and traits and ancillary information as columns, with an additional sheet containing details of sources.
- NSWFRDB had no mechanism for updating taxonomy.
- For some sources, the original data were conserved as recorded, in many other cases, original source data were modified prior to entry into the database based on general principles (Kenny et al. 2004), but record-specific operator interpretations and modifications were mostly undocumented and therefore not readily repeated.
- NSWFRDB lacked a standard vocabulary, generating additional sources of uncertainty related to potential inconsistencies among data sources and data entry sessions.
- Formatting constraints were not applied to the data as entered, leading to inconsistencies such as multiple codes applied to the same trait value and text comments confounded with trait values, placing severe constraints on functionality of the database.
- Many of the sources are not discoverable, precluding verification and access to contextual information.
- NSWFRDB includes undocumented duplication of sources. A number of major data sources were, themselves, compilations of other sources that were also included within the database. This biases summaries of the most commonly recorded fire response traits by species because apparent replicates are from the same observations or inferences.
- Inconsistencies between sources for the same species could not be attributed with certainty. Potential sources of trait variation within taxa include genetic/phenotypic variation, variation in fire characteristics, variation in environmental conditions, observer and sampling errors, etc.

- NSWFRDB does not include contextual variables such as fire timing and characteristics, location and proximal weather conditions, which can be important for interpreting fire response traits. This is information available only from some of the primary sources, which can only be accessed outside the database structure.

A number of the issues listed above relate to database design, some relate to the limitations of spreadsheet platforms, others are related to quality assurance within data entry, proofing and management protocols, and still others relate to the data sources themselves.

Limitations associated with these issues have significant implications for research and management applications. For example, where discrepancies in trait values exist among sources, users have insufficient contextual information to diagnose and interpret their potential causes, including geographic or genetic variation, variation related to fire characteristics, site characteristics or proximal weather conditions, differences in trait interpretation or observer. Similarly, any attempt to summarise the most common trait values for a taxon are likely to be affected by record duplicates and inconsistent formatting of entries.

Design principles

Phase 1 of our work identified a set of principles for development of a new generation plant fire ecology trait data repository:

1. The database design should accommodate:
    a. primary field observations of traits (spatially and temporally explicit, with an identified primary observer);
    b. primary laboratory observations for traits that cannot be diagnosed except under controlled conditions (attributable to discoverable sources);
    c. secondary observations of traits (attributable to a discoverable compilation source, not necessarily spatially or temporally specific).
2. The database should include data on the observation (date, geocode, observer, etc.).
3. The data model should include relevant contextual information for primary sources to enable query filtering by source attributes.
4. The database structure should accommodate information in existing data repositories, subject to verification of sources, and QA management of duplicates.
5. A vocabulary of terms should be established to ensure consistency in framing fields and data values.
6. Guidelines should be prepared for interpreting traits and entering values in the correct fields
7. The database should be live-linked to standard and updatable sources of species nomenclature.

8. Automated error checking procedures should be developed to improve QA of data.

Phase 2

The database structure was developed according to the design principles specified in Phase 1, from plant population fire ecology concepts described in Keith (1996, 2012), Keith et al. (2002) and DAWE (2022), as well as relevant case studies in plant demography. The structure was refined iteratively with testing of example data sets collected in a range of ecosystems after the 2019-20 bushfires, and consultation with fire ecologists and managers.*Database structure*

The overall structure of the database based on version 1.0 (Ferrer & Keith 2022) is shown in Figure 4.1.

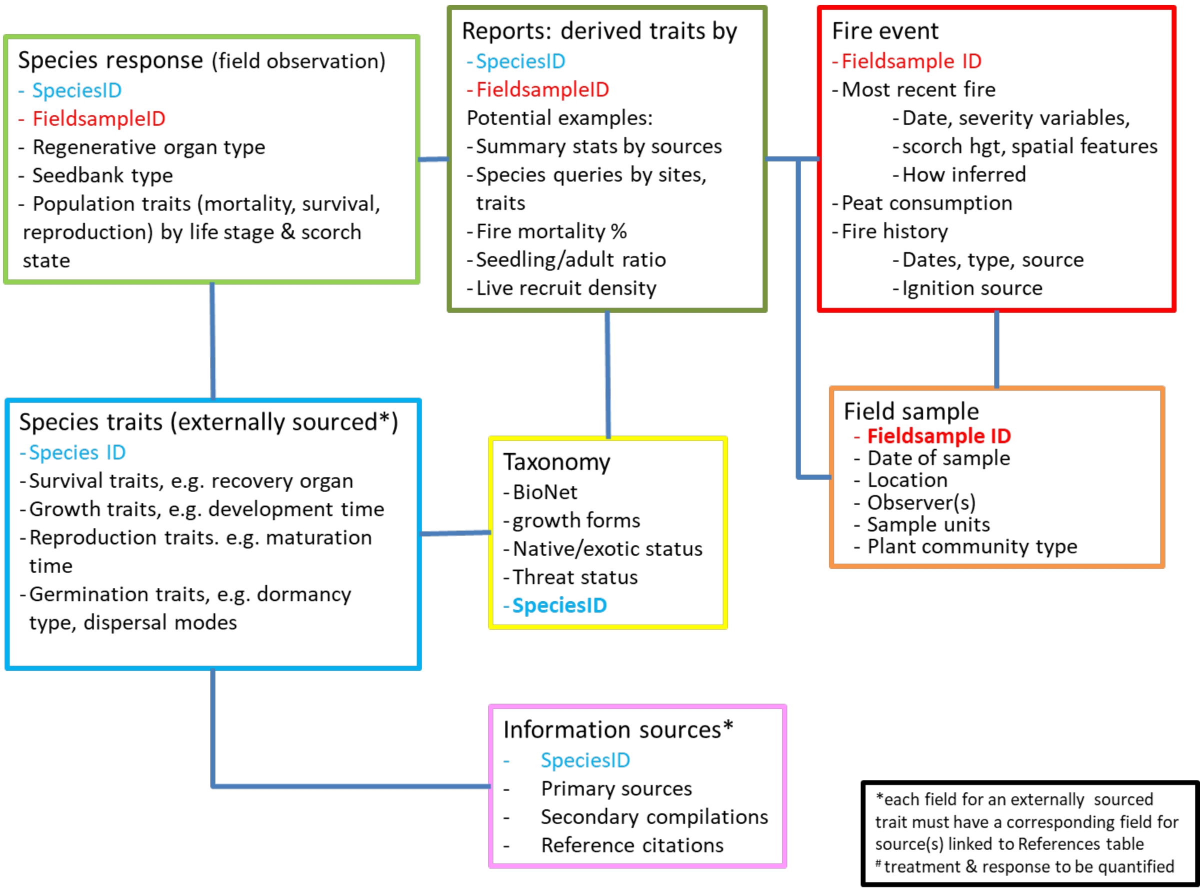


Figure 4.1. Schematic of database structure for Fire Ecology Plant Traits showing seven modules and summaries of their content.

Species trait module

Plant taxon traits (within Species traits module, Fig. 4.1) were developed in a working group of plant fire ecologists from UNSW and DCCEW using the plant life cycle as a deductive framework to identify key life-history processes that interact with fire regimes and govern responses and population and species levels (Keith 1996, 2012). The key processes were: germination; growth; survival; reproduction; dispersal; and recruitment. Multiple traits were defined to encompass fire-related variation for each life-cycle process. A set of priority plant traits was identified for inclusion in a prototype of the database. Priorities were determined by: current application in fire management; inclusion in the existing NSWFRDB repository; utility for database testing; availability of reliable primary data sources. The set of priority taxon traits increased after initiation of DCCEW's Applied Bushfire Science program in 2022 and additional traits were included in subsequent versions during phase 3. Table 1 lists the traits available within the database structure at the time of writing. Documentation includes short text definitions of each trait and its allowable values, which may be continuous, multi-state, binary or text. The database structure requires a source for each trait value and a method of estimation (direct observation, various kinds of inference). Uncertainty in trait values is represented by bounded ranges of quantitative variables or selection of multiple plausible state values.

Table 1. Plant taxon fire traits (blue module, Fig. 1) within Fire Ecology Traits for Plants version v1.0 (Ferrer & Keith 2022; http://13.54.3.205/index).

Trait code	Trait name	Life stage	Life history process	
germ8	Seed dormancy type	Seed	Germination	Info
repr3	Age at first flower production (from seed)	Standing plant	Reproduction	Info
repr4	Maturation age	Standing plant	Reproduction	Info
germ1	Seedbank Type	Seed	Germination	Info
grow1	Age to develop regenerative/resistance organs	Standing plant	Growth	Info
repr2	Post-fire flowering response	Standing plant	Reproduction	Info
rect2	Establishment pattern	Seedling	Recruitment	Info

Trait code	Trait name	Life stage	Life history process	
repr3a	Time to first post-fire reproduction (from resprouts)	Standing plant	Reproduction	Info
surv1	Resprouting - full canopy scorch	Standing plant	Survival	Info
surv4	Regenerative Organ	Standing plant	Survival	Info
surv5	Standing plant longevity (Max)	Standing plant	Survival	Info
surv6	Seedbank half-life	Seed	Survival	Info
surv7	Seed longevity	Seed	Survival	Info
disp1	Propagule dispersal mode	Seed	Dispersal	Info

Information sources

The information sources module (pale purple, Fig. 1) stores the citation details of primary information sources (those reporting original observations and inferences) and compilation sources (those in which observations are compiled from primary or other secondary sources). Each source is linked to one or more trait estimates for one or more species.

Species response (field observation) module and protocol

A key innovation of the new database structure is the incorporation of a module for handling spatially and temporally explicit field observations of fire response. Observations are gathered from a plot of user-defined dimensions appropriate to the plant growth forms present (large trees require larger plots than small forbs) and may be structured by sub-plots. The field protocol enables trait observations to be linked to a place, time and fire event(s), and enables variability in responses to be captured and related to their causal agents. It also provides an opportunity to guide the future acquisition of data in a framework that promotes consistency and utility for management and research applications, while minimising and estimating observer-related uncertainty. The observations are stored in the plant response module (green, Fig. 1). The full set of field variables are given in the field proforma (Appendix 1). In addition to observations on regenerative organs and seed bank types, the following population traits are included based on counts within field plots of specified dimensions (enabling survival and reproduction to be estimated):

- Unburnt individuals
- Living resprouting juvenile individuals
- Living resprouting adult individuals
- Reproductive living resprouting plants (subset of previous)
- Resprouted individuals that subsequently died post-fire
- Instantaneously fire-killed individuals
- Living postfire recruits
- Dead post-fire recruits

Ideally, these traits are recorded for all detectable species in the plot, but may be gathered for a single taxon or group of taxa of interest. Descriptors of vegetation structure (height, cover & dominant life forms of horizontal strata) are included to quantify ecosystem state and development.

Fire event

The fire event module (red, Fig. 1) enables fire characteristics that may influence ecological responses to be estimated and recorded on site. These include the date and igniton source (lightning, management, accidental, arson, etc.) of the most recent fire and, where possible, local evidence of the dates of prior fires, with provision to record the type of evidence (charcoal remains, local informants, etc.). Three metrics of above-ground fire severity and one measure of below-ground fire severity are included in the fire module:

- Scorch height (minimum, maximum and modal estimate in metres)
- % of plant foliage that was scorched and % that was consumed in each vegetation stratum (ground, shrub, small tree, canopy tree) within the plot
- Minimum diameter (in mm) of remaining twigs within c. 1 m of ground level (10 replicates)
- Maximum depth and extent (% of plot area) of peat consumption.

These metrics enable survival, regenerative and reproductive responses to be interpreted in relation to fire behaviour and also provide verification data for fire severity remote sensing products. Detectable evidence of fire severity declines at different rates with time since fire for different metrics. Estimates made more than 1-2 years after fire are generally of low reliability, although detectable evidence declines more rapidly for the first two metrics that the last two.

Field sample

The field sample module (orange, Fig. 1) includes details of the date of observation, geolocation co-ordinates, topographic, substrate and hydrological characteristics of the site, and names of observers. The observation date, together with the estimated date of fire (fire module), enables time since fire to be calculated. The geolocation enables geographic variation in species responses to evaluate as data accumulate across species' ranges of distribution. Site characteristics enable species responses to be placed in context of environmental gradients.

Taxonomy

The taxonomy module (yellow, Fig. 1) defines the standard nomenclature applied to taxon names. Taxon names recorded in the field are linked to the currently accepted name for the taxon based on a plant name index repository, and names are updated according to the latest release of the standard index. Version 1.0 of the database uses NSW BioNet plant taxonomic index provided by the National Herbarium of NSW as the standard nomenclature. However, the database structure enables any national or international plant name index to be used as the taxonomic standard.

The taxonomy module also enables storage of ancillary information linked to plant names, including growth form, threat status, distribution map, etc. Version 1.0 (Ferrer & Keith 2022) includes current threat status from listings under the Australian *Environment Protection and Biodiversity Conservation Act 1999* and the NSW *Biodiversity Conservation Act 2016*, and current distribution information from the Atlas of Living Australia (https://www.ala.org.au/).

Reporting

The reporting module (dark green, Fig. 4.1) enables queries and reports to be generated from data stored in combinations of other modules. Functionality in version 1.0 is limited to simple exports of species by traits and visual display tables (e.g. Fig. 4.2).

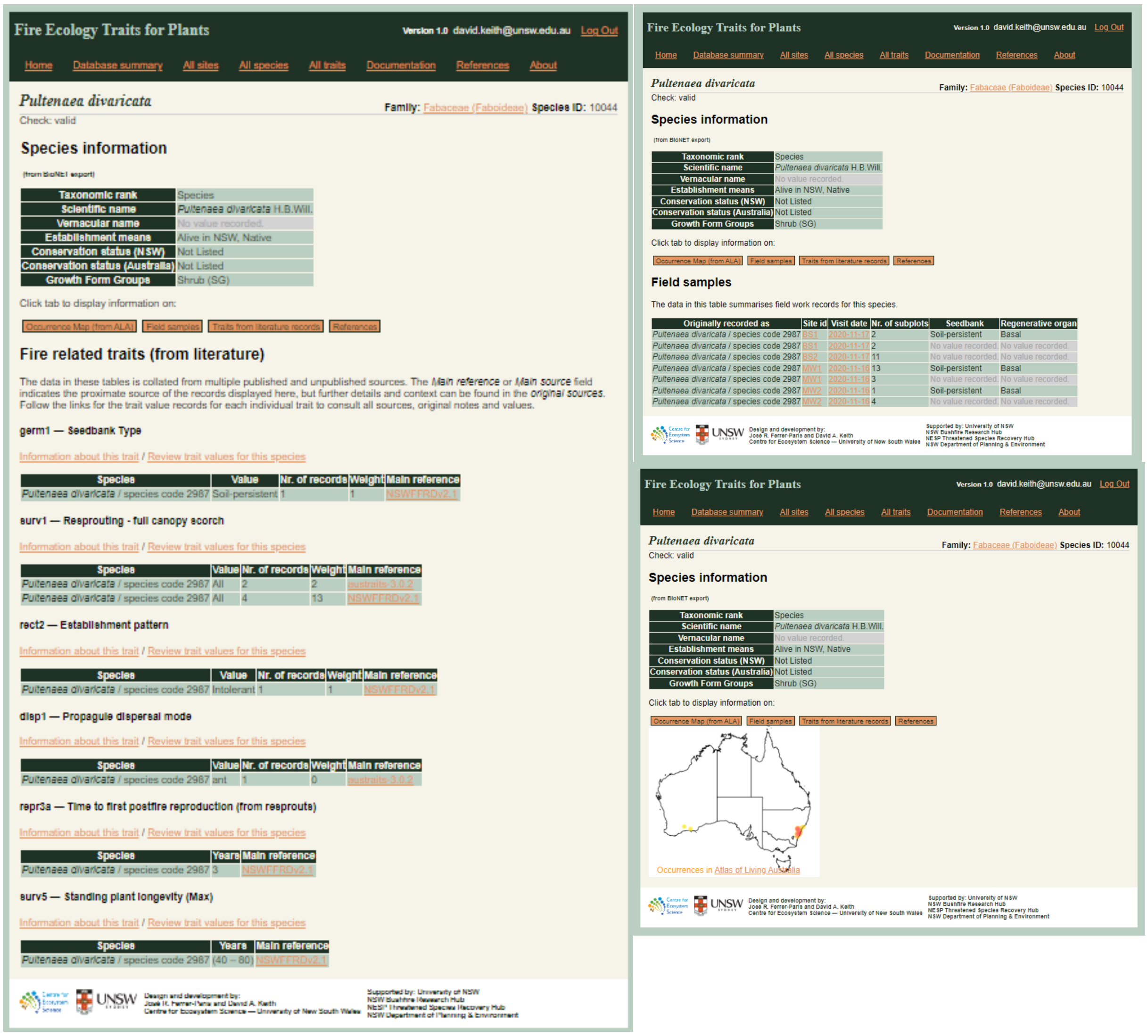


Figure 4.2. Example reports from the Species Traits, Species Response and Taxonomy modules.

Field protocol

The field protocol supporting the Species Response module of the database was developed by leveraging support from the Commonwealth Wildlife and Habitat Bushfire Recovery Program. A draft proforma was developed, trialled and refined in a wide range of recently burnt ecosystems, including heathlands, eucalypt forests, rainforests and wetlands. Design of the protocol drew from extensive long term ecological research studies in fire ecology led by UNSW (Lindenmayer et al. 2014). As noted above, the protocol employs standardised methods Fieldwork was undertaken during 2020 and 2021 in northeast NSW, the Sydney basin, southeast NSW and southwest NSW, mostly within the footprint of the 2019-20 bushfires by field teams comprising UNSW staff and students, consultants and DCCEW collaborators.

At the time of writing, version 1.0 of the database (Ferrer & Keith 2022) includes new systematic plots at 115 locations surveyed by the UNSW team and its collaborators, including several dozen that sample Threatened Ecological Communities listed under the BC Act (Table 2). These include trait values for 874 plant species from 136 families, including listed.

Table 2. New systematic post-fire survey plots with trait data incorporated into Fire ecology Traits for Plants database version 1.0 as at 2022. (*include plots sampling Threatened Ecological Communities listed under the NSW BC Act 2016 and/or EPBC Act 1999)

Survey	Number of sites
Kosciuszko NP - Alpine Bogs*	6
Kosciuszko NP - Alpine ash forests	8
Newnes plateau – upland swamps*	20
Nightcap, Tooloom NP & related areas	
– Complex & simple subtropical Rainforests*	17
Sassafras – temperate rainforests*	2
Monga NP – Nadgee NR – cool temperate rainforests	5
Blue mountains & southern highlands – wet sclerophyll forests*	28
Yatteyattah NR – dry rainforests*	7
Various locations Sydney Basin – heathlands, dry sclerophyll	22
	115

Further surveys are continuing by the UNSW team and by the DCCEW Applied Bushfire Science team and are being processed for incorporation into the data base.

Phase 3

The initiation of DCCEW's Applied Bushfire Science program in early 2022 drove a need to accelerate implementation of greater functionality and secure and rapid access to the database. Phase 3 of database development addressed these objectives.

Open-access web application

Development versions of the database were housed on a UNSW server, which limited accessibility to external users. The database had been constructed in a format compatible with the NSW BioNet biodiversity information system to enable its later integration by DCCEW information technology specialists. However, more rapid accessibility was required than could be achieved through an extended integration into corporate systems. In consultation with DCCEW, it was agreed that a secure web application would meet immediate needs without foreclosing options for later integration into BioNet if desired.

Phase 3 of database development implemented migration of the database from the UNSW server to an open source web application (currently at http://13.54.3.205/index, Ferrer & Keith 2022). The web application requires user registration to obtain free access to the data, and enables editing and upload of data by users assigned rights to do so to assure maintenance of data quality.

Additional functionality

In addition to development of the web application and migration of data into it, Phase 3 implemented extensions to functionality of the database to accommodate:

- multiple 'literature' records/sources per species
- bounded estimates of trait values (standard fuzzy number format)
- revisions to the systematic vocabulary for the Species Response (field observation) module to include NSW vegetation classes and formations (Keith 2004)
- data entry proformas to accommodate survival, growth, reproduction, recruitment and dispersal traits extracted from literature and related sources
- user registration and assigned editing rights
- full data export

At request of DCCEW, work began on a protocol to derive Vital Attribute functional groups (*sensu* Noble & Slatyer 1980) from trait data imported from NSWFRDB. While progress was made in mapping concepts and coding rules, poor data quality in NSWFRDB posed significant barriers to implementation, and this component was set aside until a suitable reliable dataset is available.

Caveats on datasets

The fire traits data currently within Fire Ecology Traits for Plants version 1.0 (Ferrer & Keith 2022) come from a diverse range of sources, primarily as a result of ingesting legacy data from NSWFRDB. In general, new field data within the Species Response (field observation) module is of high and consistent quality, with traits diagnosed and taxonomic identifications verified by experienced fire ecologists. In contrast, legacy data from NSWFRDB includes a range of high and low quality data, some with known errors and inconsistencies, some based on published observations and some with no apparent traceable documentation (see Review of existing data repository in Phase 1). While some errors may be traced back to original sources or compilations (e.g. identification errors, varied trait interpretations), additional errors apparently arose during diagnosis and extraction of data from primary sources, and their transcription and entry into successive NSWFRDB spreadsheets. Further errors may have arisen from the migration process due to formatting inconsistencies in NSWFRDB.

To address fitness for purpose of the legacy data, we recommend a systematic critical review of provenance and quality of legacy data sets migrated from NSWFRDB to:

1. isolate high-quality primary data sources as independent entries in the new database;
2. identify and retire data sources of low quality (e.g. insufficient documentation for verification and provenance, inconsistent trait diagnoses, unreliable taxonomic identifications, etc.);
3. exclude duplicate records of the same primary observations migrated from different compilation sources; and
4. correct known and verified errors diagnosed by consulting primary sources or observers.

The review and remediation of datasets should be prioritised to verify published primary sources with potentially high quality data.

Part 2. Plant population responses to fire

Mark Ooi and David Keith

Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, UNSW

Background

Another part of the WP4 core project was to address key knowledge gaps relevant to fire management for biodiversity conservation in NSW by developing knowledge infrastructure to resolve Thresholds of Potential Concern (TPC) in fire regimes for conservation of threatened biodiversity. While NSW agencies were among the first to implement this innovative approach to fire management, successful outcomes have been severely hampered by limited data. TPCs are defined only at a generic level for major vegetation formations, with species-specific information limited to very few well-studied taxa. This information is critical to fulfil statutory responsibilities for threatened species conservation.

Hundreds of threatened species in NSW are at risk from adverse fire regimes, however a fundamental understanding of the impacts that different fire regime elements have is lacking. Furthermore, TPCs implemented in NSW management frameworks are essentially limited to fire frequency. Thresholds for other fire regime components including season, severity and spatial configuration are essentially undefined, yet critical to inform management the persistence of biodiversity.

Characterisation of sensitivities to different fire regime elements

Fire season

The impact of fire frequency has been the focus of numerous studies, with a decrease in the intervals between fires limiting to persistence of obligate-seeding shrub species with long primary juvenile periods (Ooi et al., 2022). Projected changes to climate could exacerbate this interval squeeze (Enright et al., 2015; Fairman et al., 2016). Nevertheless, other fire regime factors, such as season and severity, can also undoubtedly affect plant population persistence and recovery (e.g. Ooi et al. 2014; Tangney et al. 2022) but there are few empirical studies measuring these effects over long time periods (Ooi, 2019). Furthermore, managed burns are a primary source of fire in natural systems and are shifting fire season away from the peak time of natural wildfire. Understanding fire season effects are particularly important for managing threatened species, to ensure that prescriptions provide the best conditions for persistence of the target species. We established a research programme that targeted this question, utilising linkages with partners at NSW DPIE, as well as interstate collaborators in WA DBCA, Queensland Fire and Biodiversity Consortium and SA DEW.

We found impacts of shifting fire seasons on three different plant groups; species with physiologically dormant seeds, post-fire flowering and resprouting species. However the magnitude of impact varied between functional groups.

Species with physiologically dormant seeds, which is a type of dormancy dominant in threatened shrub species from fire-prone regions of NSW (Ooi, 2007; Collette & Ooi, 2021a), were identified as one group which were particularly sensitive to season of burn. This was reported from studies on threatened species *Asterolasia buxifolia*, *Leucopogon exolasius* and *Boronia keysii* (Queensland listing), and rare NSW endemics *Boronia floribunda*, *B. fraseri* and *B. serrulata*, as well as a number of common species closely related to these (Ooi, 2019; Collette & Ooi, 2017, 2021b; Mackenzie et al., 2021). It should be noted that species with physically dormant seeds (i.e. "hard-seeded" species such as most species in the Fabaceae) displayed few differences in response to different fire seasons (Collette & Ooi, 2021a).

The main negative impact that could result for physiologically dormant species being burnt in inappropriate seasons is reduced or delayed seedling recruitment. Some evidence from our work highlights that this can delay growth and/or maturation of the population (Ooi 2019; Nolan et al. 2021). This effectively means that the primary juvenile period will increase and minimum tolerable thresholds need to be increased if a preceding burn was out-of-season (i.e. out of the typical peak fire season in the region). Obligate-seeding species (those that have individuals killed by the passage of fire) would likely suffer the biggest impact at least in the short term, as they are dependent entirely on recruitment from the seed bank.

Post-fire flowering species and other resprouting species were also impacted by different season of burn. This included a higher proportion of the population flowering for the Gymea Lily (*Doryanthes excelsa*) and *Lambertia formosa* after autumn compared to spring fires (Paroissien & Ooi, 2021; Thomsen & Ooi 2022). It is assumed that reduced flowering would lead to reduced recruitment. While these species all persist via resprouting, meaning that fire season impacts are less likely to have short-term negative consequences, consistent (in this case) autumn burns may lead to decline.

Conclusions

fire seasonality and threatened species

The impacts of fires in different seasons on germination can vary in strength and direction, depending on the species (Mackenzie et al. 2021). It is therefore difficult to identify a season of burn to avoid without knowing the species-specific response. We recommend that a **precautionary approach** therefore be used with regards to season of burn, **particularly for species that may be most susceptible; threatened obligate seeding species with physiological seed dormancy**. Recommendations are: i) if data are available on a threatened species' season-of-burn response, then refer to this prior to implementing a burn and avoid burning in seasons likely to cause population declines, ii) where possible and where data highlight a potential impact, avoid burning during the season where risk of population decline is greatest in planning, iii) if no data are available, or it is difficult to schedule a burn in a particular season, ensure that a patch with potentially susceptible species are not burnt in the same out-of-season period more than twice in a row (i.e. if a patch has previously been bunt in spring HRs in the past, try to make the subsequent HR an autumn burn).

Extreme fire severity and relative extent

Wildfires around the world are continuing to break records in terms of size and severity, driven in part by climate change (Le Breton et al. 2022). In Australia, unprecedented fires during the 2019-20 bushfire season burnt the largest area of forest in temperate ecosystems on record (Boer et al., 2020). The sheer extent of the fires means that assessing biodiversity impacts is a challenge. However, this same factor also represented a unique opportunity, providing landscape-scale study areas for evaluating interactions between extreme fire severity and prior fire history.

We quantified the impacts of increasing fire severity on functional groups based on several traits including seed bank type (focusing on serotinous species, i.e. those with canopy-stored seed banks), seed size and fire sensitivity. This was done to improve predictions by identifying those groups (and therefore threatened species within these groups) at increased risk from future fire regimes and those that are more resilient. While high severity fires are a common occurrence in temperate fire-prone regions of NSW, the impacts of large extents of extremely severe fires have not often been quantified.

Like the fire season impacts outlined above, fire severity can also impact species differently, with novel traits (with regards to fire response) including seed size, cone wall thickness and seed mortality temperature threshold all potentially determining variation in recovery between species (Palmer et al., 2018; Le Breton et al., 2020). However, quantification of traits like these have been limited to very few species. It is likely that depending on the traits a species possesses, recovery time post-fire will vary depending on fire severity (Nolan et al., 2022).

We found the common species with canopy-stored seed banks, *Petophile pulchella* and *Isopogon anemonifolius* to be negatively impacted at extreme compared to low severity burned sites (Goldman & Ooi, in prep); both these species have thin-walled cones and other *Banksia* species assessed were not impacted. We also found that for species with soil seed banks, smaller-seeded species were more likely to suffer reduced recruitment at extreme compared to lower fire severities, presumably due to lethal temperatures produced in the upper layers of the soil profile (Sano et al. in review). Finally, we have recorded high rates of mortality (even complete mortality at some sites) for rainforest elements ofwet sclerophyll forests impacted by extreme fire severity (Thomsen & Ooi, in prep). Conversely, populations of co-occurring Eucalyptus species remained relatively intact.

Extreme fire events

The likelihood of extremely high severity fires over large extents are projected to increase in the future. Our findings have produced two key recommendations for the management of vegetation and component threatened species in the wake of such events. Firstly, threatened species with traits that make them vulnerable to negative impacts from large extreme severity fires should be prioritised during post-fire recovery. This would include obligate-seeding species that are serotinous, with canopy seed banks retained in thin-walled cones. Similarly, soil seed banking obligate seeders with small seed sizes (e.g. < 5mg) could also be at risk, and should be prioritised for monitoring. Secondly, while many species persist after extreme fire severity, it is likely that recruitment will be reduced in other species. This means that a longer recovery period could provide subsequent smaller populations more time to replenish their seed banks to pre-fire levels. Minimum frequency thresholds in areas previously subjected to extreme fire severity should therefore be increased where possible in order to allow sufficient recovery of plant populations.

Key Outputs

Collette, JC, Ooi, MKJ (2021) Investigation of 18 physiologically dormant Australian native species: germination response, environmental correlations and the implications for conservation. *Seed Science Research* **31**, 30-38.

For physiologically dormant (PD) species in fire-prone environments, dormancy can be both complex due to the interaction between fire and seasonal cues, and extremely deep due to long intervals between recruitment events. Due to this complexity, there are knowledge gaps particularly surrounding the dormancy depth and cues of long-lived perennial PD species. This can be problematic for both in situ and ex situ species management. We used germination experiments that tested seasonal temperature, smoke, dark and heat for 18 PD shrub species distributed across temperate fire-prone Australia and assessed how germination was correlated with environmental factors associated with their home environments. We found extremely high levels of dormancy, with only eight species germinating above 10% and three species producing no germination at all. Seven of these eight species had quite specific seasonal temperature requirements and/or very strong responses to smoke cues. The maximum germination for each species was positively correlated with the mean temperature of the source population but negatively correlated with rainfall seasonality and driest months. The strong dependence on a smoke cue for some of the study species, along with examples from other studies, provides evidence that an obligate smoke response could be a fire-adapted germination cue. Germination response correlated with rainfall season of the source populations is a pattern which has often been assumed but little comparative data across sites with different rainfall seasonality exists. Further investigation of a broader range of species from different rainfall season environments would help to elucidate this knowledge gap.

Gallagher, RV, Allen, S, Mackenzie, BDE, Yates, CJ, Gosper, CR, Keith, DA, Merow, C, White, MD, Wenk, E, Maitner, BS, He, K, Adams, VM, Auld, TD (2021) High fire frequency and the impact of the 2019-2020 megafires on Australian plant diversity. *Diversity and Distributions* **27**, 1166-1179.

Aim: To quantify the impact of the 2019–2020 megafires on Australian plant diversity by assessing burnt area across 26,062 species ranges and the effects of fire history on recovery potential. Further, to exemplify a strategic approach to prioritizing plant species affected by fire for recovery actions and conservation planning at a national scale.

Location: Australia.

Methods: We combine data on geographic range, fire extent, response traits and fire history to assess the proportion of species ranges burnt in both the 2019–2020 fires and the past.

Results: Across Australia, suitable habitat for 69% of all plant species was burnt (17,197 species) by the 2019–2020 fires and herbarium specimens confirm the presence of 9,092 of these species across the fire extent since 1950. Burnt ranges include those of 587 plants listed as threatened under national legislation (44% of Australia's threatened plants). A total of 3,998 of the 17,197 fire-affected species are known to resprout after fire, but at least 2,928 must complete their entire life cycle—from germinant to reproducing adult—prior to subsequent fires, as they are killed by fire. Data on previous fires show that, for 257 species, the historical intervals between fire events across their range are likely too short to allow regeneration. For a further 411 species, future fires during recovery will increase extinction risk as current populations are dominated by immature individuals.

Main conclusion: Many Australian plant species have strategies to persist under certain fire regimes, and will recover given time, suitable conditions and low exposure to threats. However, short fire intervals both before and after the 2019–2020 fire season .pose a serious risk to the recovery of at least 595 species. Persistent knowledge gaps about species fire response and post-fire population persistence threaten the effective long-term management of Australian vegetation in an increasingly pyric world.

Keith, DA, Benson, DH, Baird, IRC, Watts, L, Simpson, CC, Krogh, M, Gorissen, S, Ferrer-Paris, JR, Mason, TJ (2023) Effects of interactions between anthropogenic stressors and recurring perturbations on ecosystem resilience and collapse. *Conservation Biology* **37**,

Insights into declines in ecosystem resilience and their causes and effects can inform preemptive action to avoid ecosystem collapse and loss of biodiversity, ecosystem services, and human well-being. Empirical studies of ecosystem collapse are rare and hampered by ecosystem complexity, nonlinear and lagged responses, and interactions across scales. We investigated how an anthropogenic stressor could diminish ecosystem resilience to a recurring perturbation by altering a critical ecosystem driver. We studied groundwater-dependent, peat-accumulating, fire-prone wetlands known as upland swamps in southeastern Australia. We hypothesized that underground mining (stressor) reduces resilience of these wetlands to landscape fires (perturbation) by diminishing groundwater, a key ecosystem driver. We monitored soil moisture as an indicator of ecosystem resilience during and after underground mining. After landscape fire, we compared responses of multiple state variables representing ecosystem structure, composition, and function in swamps within the mining footprint with unmined reference swamps. Soil moisture declined without recovery in swamps with mine subsidence (i.e., undermined), but was maintained in reference swamps over 8 years (effect size 1.8). Relative to burned reference swamps, burned undermined swamps showed greater loss of peat via substrate combustion; reduced cover, height, and biomass of regenerating vegetation; reduced postfire plant species richness and abundance; altered plant species composition; increased mortality rates of woody plants; reduced postfire seedling recruitment; and extirpation of a hydrophilic animal. Undermined swamps therefore showed strong symptoms of postfire ecosystem collapse, whereas reference swamps regenerated vigorously. We found that an anthropogenic stressor diminished the resilience of an ecosystem to recurring perturbations, predisposing it to collapse. Avoidance of ecosystem collapse hinges on early diagnosis of mechanisms and preventative risk reduction. It may be possible to delay or ameliorate symptoms of collapse or to restore resilience, but the latter appears unlikely in our study system due to fundamental alteration of a critical ecosystem driver.

Le Breton, TD, Lyons, MB, Nolan, RH, Penman, T, Williamson, GJ, Ooi, MKJ (2022) Megafire-induced interval squeeze threatens vegetation at landscape scales. *Frontiers in Ecology and the Environment* **20**, 327-334.

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.

Mackenzie, BDE, Auld, TD, Keith, DA, Ooi, MKJ (2021) Fire Seasonality, Seasonal Temperature Cues, Dormancy Cycling, and Moisture Availability Mediate Post-fire Germination of Species With Physiological Dormancy. *Frontiers in Plant Science* **12**,

Fire seasonality (the time of year of fire occurrence) has important implications for a wide range of demographic processes in plants, including seedling recruitment However, the underlying mechanisms of fire-driven recruitment of species with physiological seed dormancy remain poorly understood, limiting effective fire and conservation management, with insights hampered by common methodological practices and complex dormancy and germination requirements. We sought to identify the mechanisms that regulate germination of physiologically dormant species in nature and assess their sensitivity to changes in fire seasonality. We employed a combination of laboratory-based germination trials and burial-retrieval trials in natural populations of seven species of Boronia (Rutaceae) to characterize seasonal patterns in dormancy and fire-stimulated germination over a 2-year period and synthesized the observed patterns into a conceptual model of fire seasonality effects on germination. The timing and magnitude of seedling emergence was mediated by seasonal dormancy cycling and seasonal temperature cues, and their interactions with fire seasonality, the degree of soil heating expected during a fire, and the duration of imbibition. Primary dormancy was overcome within 4–10 months' burial and cycled seasonally. Fire-associated heat and smoke stimulated germination once dormancy was alleviated, with both cues required in combination by some species. For some species, germination was restricted to summer temperatures (a strict seasonal requirement), while others germinated over a broader seasonal range of temperatures but exhibited seasonal preferences through greater responses at warmer or cooler temperatures. The impacts of fires in different seasons on germination can vary in strength and direction, even between sympatric congeners, and are strongly influenced by moisture availability (both the timing of post-fire rainfall and the duration soils stay moist enough for germination). Thus, fire seasonality and fire severity (via its effect on soil heating) are expected to significantly influence postfire emergence patterns in these species and others with physiological dormancy, often leading to "germination interval squeeze." Integration of these concepts into current fire management frameworks is urgently required to ensure best-practice conservation. This is especially pertinent given major, ongoing shifts in fire seasonality and rainfall patterns across the globe due to climate change and increasing anthropogenic ignitions.

Ooi, MKJ (2019) The importance of fire season when managing threatened plant species: A long-term case-study of a rare *Leucopogon* species (Ericaceae). *Journal of Environmental Management* **236**, 17-24.

Implemented burns are a primary source of fire in natural systems and occur outside of the wildfire season. However, the impacts of fire season shift on native plant species are rarely studied. Understanding fire season effects are particularly important for managing threatened species, which are often the focus of managed burns. To assess the impacts of fire seasonality and identify potential limiting traits, I studied the threatened *Leucopogon exolasius* and two common congeners, all of which persist via fire-driven population dynamics. All species were monitored over a 16 year period to assess seedling survival, growth and primary juvenile period after fire. For *L. exolasius* and the common *L. esquamatus*, comparisons of survival, growth and maturation were made after winter and summer fires, to assess the effects of season of burn. A key difference was found in primary juvenile period, which was exceptionally long for *L. exolasius* (>11 years for 80% of the population to flower) compared to the common congeners (3.2–7.57 years). Seasonal seed dormancy mechanisms meant that winter fires delayed emergence, leading to increases in primary juvenile period for both species. A long primary juvenile period may limit *L. exolasius* population persistence because plants are more likely to be killed by subsequent fire before maturation, while seasonal dormancy cues is a trait that would exacerbate the effects of this interval squeeze. In fire-prone systems, fire frequency is the key factor assumed to drive persistence, however, interactions with fire season can influence recruitment success. There are scant data on recruitment variation in response to fire seasonality, a factor that may have broad implications for rare and common species with seasonal germination requirements.

Tangney, R, Miller, RG, Enright, NJ, Fontaine, JB, Merritt, DJ, Ooi, MKJ, Ruthrof, KX, Miller, BP (2020) Seed Dormancy Interacts with Fire Seasonality Mechanisms. *Trends in Ecology & Evolution* **35**, 1057-1059.

We recently published a framework of demographic mechanisms that may impact plant population responses to changes in fire seasonality. This framework now includes eight mechanisms identified. Subsequently, Cao et al. have proposed that seed dormancy class, based on the dormancy classification scheme of Baskin and Baskin, should be recognised as an additional mechanism. Cao et al. described for each seed dormancy class, how seed dormancy induction and loss, and germination timing, may be influenced by seasonal environmental cues (e.g., light and temperature) and, separately, how they interact with fire-related cues (e.g., heat and smoke). We agree that seed dormancy and germination traits are important to the regeneration of plants in fire-prone regions. However, as Cao et al. do not identify how seed dormancy class determines seasonally varying resistant or vulnerable states required to create a fire seasonality effect beyond those already defined, it is not clear how dormancy class forms a new separate mechanism under a demographic framework.

Tangney, R, Paroissien, R, Le Breton, TD, Thomsen, A, Doyle, CAT, Ondik, M, Miller, RG, Miller, B, Ooi, MKJ (2022) Success of post-fire plant recovery strategies varies with shifting fire seasonality. *Communications Earth & Environment* **3**,

Wildfires are increasing in size and severity and fire seasons are lengthening, largely driven by climate and land-use change. Many plant species from fire-prone ecosystems are adapted to specific fire regimes corresponding to historical conditions and shifts beyond these bounds may have severe impacts on vegetation recovery and long-term species persistence. Here, we conduct a meta-analysis of field-based studies across different vegetation types and climate regions to investigate how post-fire plant recruitment, reproduction and survival are affected by fires that occur outside of the historical fire season. We find that fires outside of the historical fire season may lead to decreased post-fire recruitment, particularly in obligate seeding species. Conversely, we find a general increase in post-fire survival in resprouting species. Our results highlight the trade-offs that exist when considering the effects of changes in the seasonal timing of fire, an already present aspect of climate-related fire regime change.

Thomsen, AM, Ooi, MKJ (2022) Shifting season of fire and its interaction with fire severity: Impacts on reproductive effort in resprouting plants. *Ecology and Evolution* **12**,

Fire regimes shape plant communities but are shifting with changing climate. More frequent fires of increasing intensity are burning across a broader range of seasons. Despite this, impacts that changes in fire season have on plant populations, or how they interact with other fire regime elements, are still relatively understudied. We asked (a) how does the season of fire affect plant vigor, including vegetative growth and flowering after a fire event, and (b) do different functional resprouting groups respond differently to the effects of season of fire? We sampled a total of 887 plants across 36 sites using a space-for-time design to assess resprouting vigor and reproductive output for five plant species. Sites represented either a spring or autumn burn, aged one to three years old. Season of fire had the clearest impacts on flowering in *Lambertia formosa* with a 152% increase in the number of plants flowering and a 45% increase in number of flowers per plant after autumn compared with spring fires. There were also season × severity interactions for total flowers produced for *Leptospermum polygalifolium* and *L. trinervium* with both species producing greater flowering in autumn, but only after lower severity fires. Severity of fire was a more important driver in vegetative growth than fire season. Season of fire impacts have previously been seen as synonymous with the effects of fire severity; however, we found that fire season and severity can have clear and independent, as well as interacting, impacts on post-fire vegetative growth and reproductive response of resprouting species. Overall, we observed that there were positive effects of autumn fires on reproductive traits, while vegetative growth was positively related to fire severity and pre-fire plant size.

Full publication list

Auld, TD, Keith, DA, Gallagher, RV, Tozer, M, Ooi, MKJ, Le Breton, T, Allen, S, Yates, C, van Leeuwen, S, Williams, RJ, Mackenzie, BDE (2022) Frameworks for identifying priority plants and ecosystems most impacted by major fires. *Australian Journal of Botany* **70**, 455-493.

Bendall, ER, Bedward, M, Boer, M, Clarke, H, Collins, L, Leigh, A, Bradstock, RA (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.

Bendall, ER, Bedward, M, Boer, M, Clarke, H, Collins, L, Leigh, A, Bradstock, RA (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**,

Bliss, A, Prior, LD, Bowman, D (2021) Lack of reliable post-fire recovery mechanisms makes the iconic Tasmanian conifer Athrotaxis cupressoides susceptible to population decline. *Australian Journal of Botany* **69**, 162-173.

Bowman, D, Bliss, A, Bowman, CJW, Prior, LD (2019) Fire caused demographic attrition of the Tasmanian palaeoendemic conifer Athrotaxis cupressoides. *Austral Ecology* **44**, 1322-1339.

Bowman, D, Williamson, GJ, Johnston, FH, Bowman, CJW, Murphy, BP, Roos, CI, Trauernicht, C, Rostron, J, Prior, LD (2022) Population collapse of a Gondwanan conifer follows the loss of Indigenous fire regimes in a northern Australian savanna. *Scientific Reports* **12**,

Chan, JCS, Ooi, MKJ, Guja, LK (2022) Polyploidy but Not Range Size Is Associated With Seed and Seedling Traits That Affect Performance of Pomaderris Species. *Frontiers in Plant Science* **12**,

Collette, JC, Ooi, MKJ (2020) Evidence for physiological seed dormancy cycling in the woody shrub Asterolasia buxifolia and its ecological significance in fire-prone systems. *Plant Biology* **22**, 745-749.

Collette, JC, Ooi, MKJ (2021) Distribution of seed dormancy classes across a fire-prone continent: effects of rainfall seasonality and temperature. *Annals of Botany* **127**, 613-620.

Collette, JC, Ooi, MKJ (2021) Investigation of 18 physiologically dormant Australian native species: germination response, environmental correlations and the implications for conservation. *Seed Science Research* **31**, 30-38.

Davies, HF, Visintin, C, Murphy, BP, Ritchie, EG, Banks, SC, Davies, ID, Bowman, D (2023) Pyrodiversity trade-offs: A simulation study of the effects of fire size and dispersal ability on native mammal populations in northern Australian savannas. *Biological Conservation* **282**,

Dickman, LT, Jonko, AK, Linn, RR, Altintas, I, Atchley, AL, Bar, A, Collins, AD, Dupuy, JL, Gallagher, MR, Hiers, JK, Hoffman, CM, Hood, SM, Hurteau, MD, Jolly, WM, Josephson, A, Loudermilk, EL, Ma, W, Michaletz, ST, Nolan, RH, O'Brien, JJ, Parsons, RA, Partelli-Feltrin, R, Pimont, F, de Dios, VR, Restaino, J, Robbins, ZJ, Sartor, KA, Schultz-Fellenz, E, Serbin, SP, Sevanto, S, Shuman, JK, Sieg, CH, Skowronski, NS, Weise, DR, Wright, M, Xu, CG, Yebra, M, Younes, N (2023) Integrating plant physiology into simulation of fire behavior and effects. *New Phytologist* **238**, 952-970.

Dunker, B, Bull, CM, Keith, DA, Driscoll, DA (2019) Season of fire influences seed dispersal by wind in a serotinous obligate seeding tree. *Plant Ecology* **220**, 405-416.

Falster, D, Gallagher, R, Wenk, EH, Wright, IJ, Indiarto, D, Andrew, SC, Baxter, C, Lawson, J, Allen, S, Fuchs, A, Monro, A, Kar, F, Adams, MA, Ahrens, CW, Alfonzetti, M, Angevin, T, Apgaua, DMG, Arndt, S, Atkin, OK, Atkinson, J, Auld, T, Baker, A, von Balthazar, M, Bean, A, Blackman, CJ, Bloomfeld, K, Bowman, D, Bragg, J, Brodribb, TJ, Buckton, G, Burrows, G, Caldwell, E, Camac, J, Carpenter, R, Catford, J, Cawthray, GR, Cernusak, LA, Chandler, G, Chapman, AR, Cheal, D, Cheesman, AW, Chen, SC, Choat, B, Clinton, B, Clode, PL, Coleman, H, Cornwell, WK, Cosgrove, M, Crisp, M, Cross, E, Crous, KY, Cunningham, S, Curran, T, Curtis, E, Daws, MI, DeGabriel, JL, Denton, MD, Dong, N, Du, PZ, Duan, HL, Duncan, DH, Duncan, RP, Duretto, M, Dwyer, JM, Edwards, C, Esperon-Rodriguez, M, Evans, JR, Everingham, SE, Farrell, C, Firn, J, Fonseca, CR, French, B, Frood, D, Funk, JL, Geange, SR, Ghannoum, O, Gleason, SM, Gosper, CR, Gray, E, Groom, PK, Grootemaat, S, Gross, C, Guerin, G, Guja, L, Hahs, AK, Harrison, MT, Hayes, PE, Henery, M, Hochuli, D, Howell, J, Huang, G, Hughes, L, Huisman, J, Ilic, J, Jagdish, A, Jin, D, Jordan, G, Jurado, E, Kanowski, J, Kasel, S*et al.* (2021) AusTraits, a curated plant trait database for the Australian flora. *Scientific Data* **8**,

Foulkes, JA, Prior, LD, Leonard, SWJ, Bowman, D (2021) Demographic Effects of Severe Fire in Montane Shrubland on Tasmania's Central Plateau. *Fire-Switzerland* **4**,

Franklin, MJM, Major, RE, Bedward, M, Bradstock, RA (2021) Relative avian mobility linked to use of fire-affected resources in forested landscapes. *Forest Ecology and Management* **497**,

Franklin, MJM, Major, RE, Bedward, M, Price, OF, Bradstock, RA (2022) Forest avifauna exhibit enduring responses to historical high-severity wildfires. *Biological Conservation* **269**,

Franklin, MJM, Major, RE, Bradstock, RA (2021) How much survey effort is required to assess bird assemblages in fire-prone eucalypt forests using acoustic recorders? *Wildlife Research* **48**, 414-421.

Franklin, MJM, Major, RE, Bradstock, RA (2023) Canopy cover mediates the effects of a decadal increase in time since fire on arboreal birds. *Biological Conservation* **277**,

Furlaud, JM, Prior, LD, Williamson, GJ, Bowman, D (2021) Bioclimatic drivers of fire severity across the Australian geographical range of giant Eucalyptus forests. *Journal of Ecology* **109**, 2514-2536.

Furlaud, JM, Prior, LD, Williamson, GJ, Bowman, D (2021) Fire risk and severity decline with stand development in Tasmanian giant Eucalyptus forest. *Forest Ecology and Management* **502**,

Gallagher, RV, Allen, S, Mackenzie, BDE, Yates, CJ, Gosper, CR, Keith, DA, Merow, C, White, MD, Wenk, E, Maitner, BS, He, K, Adams, VM, Auld, TD (2021) High fire frequency and the impact of the 2019-2020 megafires on Australian plant diversity. *Diversity and Distributions* **27**, 1166-1179.

Gallagher, RV, Allen, SP, Mackenzie, BDE, Keith, DA, Nolan, RH, Rumpff, L, Gosper, CR, Pegg, G, van Leeuwen, S, Ooi, MKJ, Yates, CJ, Merow, C, Williams, RJ, Nikolopoulos, EI, Beaumont, LJ, Auld, TD (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.

Holz, A, Wood, SW, Ward, C, Veblen, TT, Bowman, D (2020) Population collapse and retreat to fire refugia of the Tasmanian endemic conifer Athrotaxis selaginoides following the transition from Aboriginal to European fire management. *Global Change Biology* **26**, 3108-3121.

Kattge, J, Bonisch, G, Diaz, S, Lavorel, S, Prentice, IC, Leadley, P, Tautenhahn, S, Werner, GDA, Aakala, T, Abedi, M, Acosta, ATR, Adamidis, GC, Adamson, K, Aiba, M, Albert, CH, Alcantara, JM, Alcazar, CC, Aleixo, I, Ali, H, Amiaud, B, Ammer, C, Amoroso, MM, Anand, M, Anderson, C, Anten, N, Antos, J, Apgaua, DMG, Ashman, TL, Asmara, DH, Asner, GP, Aspinwall, M, Atkin, O, Aubin, I, Baastrup-Spohr, L, Bahalkeh, K, Bahn, M, Baker, T, Baker, WJ, Bakker, JP, Baldocchi, D, Baltzer, J, Banerjee, A, Baranger, A, Barlow, J, Barneche, DR, Baruch, Z, Bastianelli, D, Battles, J, Bauerle, W, Bauters, M, Bazzato, E, Beckmann, M, Beeckman, H, Beierkuhnlein, C, Bekker, R, Belfry, G, Belluau, M, Beloiu, M, Benavides, R, Benomar, L, Berdugo-Lattke, ML, Berenguer, E, Bergamin, R, Bergmann, J, Carlucci, MB, Berner, L, Bernhardt-Romermann, M, Bigler, C, Bjorkman, AD, Blackman, C, Blanco, C, Blonder, B, Blumenthal, D, Bocanegra-Gonzalez, KT, Boeckx, P, Bohlman, S, Bohning-Gaese, K, Boisvert-Marsh, L, Bond, W, Bond-Lamberty, B, Boom, A, Boonman, CCF, Bordin, K, Boughton, EH, Boukili, V, Bowman, D, Bravo, S, Brendel, MR, Broadley, MR, Brown, KA, Bruelheide, H, Brumnich, F, Bruun, HH, Bruy, D, Buchanan, SW, Bucher, SF, Buchmann, N, Buitenwerf, R, Bunker, DE, Burger, J*et al.* (2020) TRY plant trait database - enhanced coverage and open access. *Global Change Biology* **26**, 119-188.

Keith, DA (2022) Transcending the disaster paradigm: Understanding persistence of animal populations in fire-prone environments COMMENT. *Global Change Biology* **28**, 341-342.

Keith, DA, Allen, SP, Gallagher, RV, Mackenzie, BDE, Auld, TD, Barrett, S, Buchan, A, English, V, Gosper, C, Kelly, D, McIllwee, A, Melrose, RT, Miller, B, Neldner, VJ, Simpson, CC, Tolsma, AD, Rogers, D, Leeuwen, S, White, MD, Yates, CJ, Tozer, MG (2022) Fire-related threats and transformational change in Australian ecosystems. *Global Ecology and Biogeography* **31**, 2070-2084.

Keith, DA, Benson, DH, Baird, IRC, Watts, L, Simpson, CC, Krogh, M, Gorissen, S, Ferrer-Paris, JR, Mason, TJ (2023) Effects of interactions between anthropogenic stressors and recurring perturbations on ecosystem resilience and collapse. *Conservation Biology* **37**,

Keith, DA, Dunker, B, Driscoll, DA (2020) Dispersal: The Eighth Fire Seasonality Effect on Plants. *Trends in Ecology & Evolution* **35**, 305-307.

Kirchhoff, C, Callaghan, CT, Keith, DA, Indiarto, D, Taseski, G, Ooi, MK, Le Breton, TD, Mesaglio, T, Kingsford, RT, Cornwell, WK (2021) Rapidly mapping fire effects on biodiversity at a large-scale using citizen science. *Science of the Total Environment* **755**,

Lawes, MJ, Crisp, MD, Clarke, PJ, Murphy, BP, Midgley, JJ, Russell-Smith, J, Nano, CEM, Bradstock, RA, Enright, NJ, Fontaine, JB, Gosper, CR, 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**, 114-130.

Le Breton, TD, Lyons, MB, Nolan, RH, Penman, T, Williamson, GJ, Ooi, MKJ (2022) Megafire-induced interval squeeze threatens vegetation at landscape scales. *Frontiers in Ecology and the Environment* **20**, 327-334.

Le Breton, TD, Natale, S, French, K, Gooden, B, Ooi, MKJ (2020) Fire-adapted traits of threatened shrub species in riparian refugia: implications for fire regime management. *Plant Ecology* **221**, 69-81.

Letnic, M, Roberts, B, Hodgson, M, Ross, AK, Cuartas, S, Lapwong, Y, Price, O, Sentinella, N, Webb, JK (2023) Fire severity influences the post-fire habitat structure and abundance of a cool climate lizard. *Austral Ecology*

Li, SY, Ma, HY, Ooi, MKJ (2021) Fire-Related Cues Significantly Promote Seed Germination of Some Salt-Tolerant Species from Non-Fire-Prone Saline-Alkaline Grasslands in Northeast China. *Plants-Basel* **10**,

Mackenzie, BDE, Auld, TD, Keith, DA, Ooi, MKJ (2021) Fire Seasonality, Seasonal Temperature Cues, Dormancy Cycling, and Moisture Availability Mediate Post-fire Germination of Species With Physiological Dormancy. *Frontiers in Plant Science* **12**, Mason, TJ, Popovic, GC, McGillycuddy, M, Keith, DA (2023) Effects of hydrological change in fire-prone wetland vegetation: An empirical simulation. *Journal of Ecology* **111**, 1050-1062.

McCann, JA, Keith, DA, Kingsford, RT (2022) Measuring plant biomass remotely using drones in arid landscapes. *Ecology and Evolution* **12**,

McInnes, SJ, Tangney, R, Brophy, JJ, Thordarson, P, Ooi, MKJ (2023) Does fire drive fatty acid composition in seed coats of physically dormant species? *Plant Biology* **25**, 268-275.

Miller, RG, Tangney, R, Enright, NJ, Fontaine, JB, Merritt, DJ, Ooi, MKJ, Ruthrof, KX, Miller, B (2019) Mechanisms of Fire Seasonality Effects on Plant Populations. *Trends in Ecology & Evolution* **34**, 1104-1117.

Miller, RG, Tangney, R, Enright, NJ, Fontaine, JB, Merritt, DJ, Ooi, MKJ, Ruthrof, KX, Miller, BP (2020) Fire Seasonality Effect on Post-Fire Wind Dispersal: Response to Keith, Dunker, and Driscoll. *Trends in Ecology & Evolution* **35**, 307-307.

Moreira, F, Ascoli, D, Safford, H, Adams, MA, Moreno, JM, Pereira, JMC, Catry, FX, Armesto, J, Bond, W, Gonzalez, ME, Curt, T, Koutsias, N, McCaw, L, Price, O, Pausas, JG, Rigolot, E, Stephens, S, Tavsanoglu, C, Vallejo, VR, Van Wilgen, BW, Xanthopoulos, G, Fernandes, PM (2020) Wildfire management in Mediterranean-type regions: paradigm change needed. *Environmental Research Letters* **15**,

Ondei, S, Prior, LD, McGregor, HW, Reid, AM, Johnson, CN, Vigilante, T, Goonack, C, Williams, D, Bowman, D (2021) Small mammal diversity is higher in infrequently compared with frequently burnt rainforest-savanna mosaics in the north Kimberley, Australia. *Wildlife Research* **48**, 218-229.

Ondik, MM, Bennell, M, Davies, RJP, Ooi, MKJ, Munoz-Rojas, M (2022) Fire and land use impact soil properties in a Mediterranean dry sclerophyll woodland. *Journal of Environmental Management* **324**,

Ondik, MM, Ooi, MKJ, Munoz-Rojas, M (2023) Soil microbial community composition and functions are disrupted by fire and land use in a Mediterranean woodland. *Science of the Total Environment* **895**,

Ooi, MKJ (2019) The importance of fire season when managing threatened plant species: A long-term case-study of a rare *Leucopogon* species (Ericaceae). *Journal of Environmental Management* **236**, 17-24.

Paroissien, R, Ooi, MKJ (2021) Effects of fire season on the reproductive success of the post-fire flowerer *Doryanthes excelsa*. *Environmental and Experimental Botany* **192**,

Price, OF, Mikac, K, Wilson, N, Roberts, B, Critescu, RH, Gallagher, R, Mallee, J, Donatiou, P, Webb, J, Keith, DA, Letnic, M, Mackenzie, BDW (2023) Short-term impacts of the 2019-20 fire season on biodiversity in eastern Australia. *Austral Ecology* **48**, 3-11.

Prior, LD, Bowman, D (2020) Classification of Post-Fire Responses of Woody Plants to include Pyrophobic Communities. *Fire-Switzerland* **3**, Prior, LD, Foyster, SM, Furlaud, JM, Williamson, GJ, Bowman, D (2022) Using permanent forest plots to evaluate the resilience to fire of Tasmania's tall wet eucalypt forests. *Forest Ecology and Management* **505**,

Prior, LD, Nichols, SC, Williamson, GJ, Bowman, D (2023) Post-fire restoration of Sphagnum bogs in the Tasmanian Wilderness World Heritage Area, Australia. *Restoration Ecology* **31**,

Ramos, DM, Valls, JFM, Borghetti, F, Ooi, MKJ (2019) Fire cues trigger germination and stimulate seedling growth of grass species from Brazilian savannas. *American Journal of Botany* **106**, 1190-1201.

Rodriguez-Cubillo, D, Prior, LD, Bowman, D (2020) Variation in Eucalyptus delegatensis post-fire recovery strategies: The Tasmanian subspecies is a resprouter whereas the mainland Australian subspecies is an obligate seeder. *Forest Ecology and Management* **473**,

Santos, JL, Hradsky, BA, Keith, DA, Rowe, KC, Senior, KL, Sitters, H, Kelly, LT (2022) Beyond inappropriate fire regimes: A synthesis of fire-driven declines of threatened mammals in Australia. *Conservation Letters* **15**,

Santos, JL, Sitters, H, Keith, DA, Geary, WL, Tingley, R, Kelly, LT (2022) A demographic framework for understanding fire-driven reptile declines in the 'land of the lizards'. *Global Ecology and Biogeography* **31**, 2105-2119.

Sparks, AM, Blanco, AS, Wilson, DR, Schwilk, DW, Johnson, DM, Adams, HD, Bowman, D, Hardman, DD, Smith, AMS (2023) Fire intensity impacts on physiological performance and mortality in Pinus monticola and Pseudotsuga menziesii saplings: a dose-response analysis. *Tree Physiology* **43**, 1365-1382.

Tangney, R, Miller, RG, Enright, NJ, Fontaine, JB, Merritt, DJ, Ooi, MKJ, Ruthrof, KX, Miller, BP (2020) Seed Dormancy Interacts with Fire Seasonality Mechanisms. *Trends in Ecology & Evolution* **35**, 1057-1059.

Tangney, R, Paroissien, R, Le Breton, TD, Thomsen, A, Doyle, CAT, Ondik, M, Miller, RG, Miller, B, Ooi, MKJ (2022) Success of post-fire plant recovery strategies varies with shifting fire seasonality. *Communications Earth & Environment* **3**,

Thomsen, AM, Ooi, MKJ (2022) Shifting season of fire and its interaction with fire severity: Impacts on reproductive effort in resprouting plants. *Ecology and Evolution* **12**,

Ward, M, Tulloch, A, Stewart, R, Possingham, HP, Legge, S, Gallagher, RV, Graham, EM, Southwell, D, Keith, D, Dixon, K, Yong, CJ, Carwardine, J, Cronin, T, Reside, AE, Watson, JEM (2022) Restoring habitat for fire-impacted species' across degraded Australian landscapes. *Environmental Research Letters* **17**,

Yusup, S, Sundberg, S, Ooi, MKJ, Zhang, MM, Sun, ZQ, Rydin, H, Wang, M, Feng, L, Chen, X, Bu, ZJ (2023) Smoke promotes germination of peatland bryophyte spores. *Journal of Experimental Botany* **74**, 251-264.

Zirondi, HL, Ooi, MKJ, Fidelis, A (2021) Fire-triggered flowering is the dominant post-fire strategy in a tropical savanna. *Journal of Vegetation Science* **32**,

Additional outcomes

Honours theses

Eleanor Carter (UOW October 2018):

The medium and short-term effects of fire severity on fossorial reptile communities in the Warrumbungle and Pilliga National Parks. Supervisor Owen Price

Fire is a global disturbance which affects most ecosystems. It has the ability to modify the vegetation structure and determine which species will thrive or perish. This experiment was conducted in the Warrumbungle National Park which has a history of very infrequent severe fires which cover thousands of hectares. The Pilliga Forests where the second half of this study was conducted is burnt frequently with a combination of wildfires and controlled burns that vary greatly in extent and severity. The aim of this experiment is to determine how the reptile community in the Warrumbungle National Park and Pilliga Forests (Pilliga East State Conservation Area, Pilliga National Park and Timmallallie National Park) responded to the different severities of the 2013 and 2018 wildfires respectively. The effects of fire severity on habitat, birds and mammals is well documented. However, there is no Australian literature on the effects of severity on reptiles. This study addresses the knowledge gap as the effects of fire severity on reptiles has not been studied in Australia. This study will be addressing three main questions: 1. how does fire severity affect the habitat? 2. How does fire severity affect the reptile community? 3. How does habitat affect the reptile community? Reptiles were sampled using pitfall traps, active day and night searches and baited camera traps. Data were analysed using generalised linear models and multivariate models in R. It was found that fire severity significantly affected the some of the groundcover and tree habitat variables measured as well as the four out of the five focus species and the Warrumbungles National Park. Habitat variables had a much greater effect on the abundance of reptiles than it had on reptile species richness but did not eliminate any species. The five focus species all responded differently to the habitat variables.

Braden Riles (UOW October 2018):

The Effects of Wildfire Severity on Arboreal and Semi-Arboreal Reptiles. Supervisor Owen Price (UOW)

The ecological effects of fire severity, as an aspect of the fire regime, are poorly understood despite predictions of increasing wildfire severity globally. Knowledge of the effects of fire severity upon reptiles is extremely limited, while almost nothing is known about the responses of arboreal and semi-arboreal reptiles to fire severity, despite evidence for profound effects of fire severity upon the arboreal habitat. This research aimed to quantify the effects of fire severity upon arboreal and semi-arboreal reptile assemblages by posing three key questions; 1) How does recent severe wildfire and how do variations in wildfire severity affect the assemblage of arboreal and semi-arboreal reptiles, 2) What components of the arboreal habitat are effected by recent severe wildfire and variations in fire severity and 3) How do habitat components effect the assemblage of arboreal and semi-arboreal reptiles. Reptile and habitat surveys were carried out in open dry sclerophyll forests and woodlands 5 years after a large wildfire in the Warrumbungle National Park and 3 months after a large wildfire in the Pilliga Forest of Central NSW, Australia. Sites were selected across both locations according to a stratified design, with reptile surveys making use of novel camera trapping methods, supplemented by active searches and pitfall traps. Surveys of key reptile habitat were also conducted at all sites. Results found limited evidence for an effect of fire severity upon the occurrence of any species in the Warrumbungle NP, while the occurrence of the Eastern Spiny-tailed Gecko (*Strophurus williamsi*) was positively affected by recent severe fire in the Pilliga Forest. The response of reptiles to arboreal habitat components was highly species specific, with the occurrence of species often influenced by multiple habitat components. It was also found that fire severity had a strong effect upon a large proportion of arboreal habitat components. The degree to which the arboreal habitat mediated the response of individual species to fire severity was likely due to species-specific differences in foraging and habitat requirements. It is likely that fire severity has an effect upon the abundance of individual species and that considerable post-fire recovery has occurred in the Warrumbungle NP. Future research should therefore aim to determine the interactive effects of fire severity and the time since fire on arboreal and semi-arboreal species. Although current fire regimes may not affect the occurrence of species, wildfire is predicted to become more severe and frequent, highlighting the need to further understand the responses of arboreal and semi-arboreal reptile species.

Mirima Goldman (UNSW December 2022):

How can we seed when our banks are burning? Extreme fire severity and the persistence of serotinous species. Supervisor: Mark Ooi (UNSW)

This study utilised sites impacted by the 2019-2020 bushfire season in south-eastern Australia to assess the impact of extreme fire severity on the persistence of serotinous species. It focused on six species in the Proteaceae, all native to the Upper Blue Mountains, including three obligate seeders (*Petrophile pulchella*, *Hakea dactyloides* and *Banksia cunninghamii*) and three resprouters (*Isopogon anemonifolius*, *Banksia spinulosa* and

Banksia serrata). We compared seedling recruitment across a gradient of fire severity in the field and conducted a laboratory study and used existing literature to identify temperature thresholds that seeds of serotinous species could maintain viability. Three species, *Petrophile pulchella*, *Isopogon anemonifolius* and *Banksia spinulosa*, had significantly fewer seedlings recruiting as fire severity increased. Findings from the laboratory study and previous heating experiments identified in the literature complemented the findings from the field. These results highlighted that, even amongst fire prone communities, some species could be threatened by the increases in fire severity predicted under climate change. The data generated here also contributes to the overall aims of WP4, by providing baseline data for interpreting outcomes of changes to different fire regime elements.

Cameron Kirk (UOW October 2022):

Survival and Recolonisation of Australian Mistletoes after High Severity Fire: Implications for the Warrumbungle National Park. Supervisors Owen Price (UOW) and Andrew Denham (DCCEEW)

Fire events in south-eastern Australia are increasing in frequency and severity resulting from climate change. The existing fire adaptation research for Australian flora has focussed on fire adapted lineages. However, it important to understand the dynamics of fire vulnerable species and the mechanisms by which they persist fire prone environments. Mistletoes are an example of a fire vulnerable species that lacks the ability to resprout or reseed, relying on recolonisation following fire.

This thesis furthers fire ecology by establishing a relationship between fire severity and the survival of mistletoes through the 2013 Wambelong fire in the Warrumbungle National Park. It was expected that high severity fire would eliminate mistletoe populations. This thesis also sought to identify the effect of mistletoe height, size, host fire health, host species, and ecological community mistletoe survival. It assessed this relationship through 81 transects across a diverse array of fire severities.

The thesis identified a baseline survival rate of 69.4% for unburnt regions. High severity exhibited a corrected survival of 0.351%, showing a dramatic decline in mistletoe survival. Mistletoe size, host fire health, host species and host community all exhibited significant effects on mistletoe survival. Contrary to assumptions, mistletoe height did not exhibit an effect on mistletoe survival. The thesis showed that high severity fire played an important role in determining mistletoe distribution. The findings suggest that mistletoes use edge recruitment to recolonise after high severity fire and may require a multi-decadal fire free period or risk to recover at a landscape level.

Liam Falls (UOW April 2023):

Prescribed Fire Regimes: The Immediate and Short-term Impacts Upon Susceptible Invertebrates. Supervisor Owen Price (UOW)

Prescribed fire is the predominant land management tool used across Australia's temperate forests. However, little is known about the use of periodic, low-intensity prescribed fires over long-time frames and their effect on invertebrate communities. Most invertebrate species provide essential ecosystem services and are an essential component of global food chains. Despite their profound importance to ecosystems globally, invertebrates are often ignored entirely in fire research and generally lack incorporation into fire management and recovery plans. Prescribed fire usage is poised to increase in usage to mitigate the effects of damaging wildfires under a changing climate and so its impact on invertebrates should be assessed to determine if it provides sound ecological outcomes alongside human asset protection. A multi-method sampling approach using beating trays, leaf litter collections and a custom method of observing empty pitfall traps with scouting cameras was used in this study to measure invertebrate abundances at six sclerophyll and eucalypt forest sites on the NSW South Coast which had undergone a prescribed hazard reduction burn within the last 3 years. The aim of this project was to assess the immediate and short-term impacts on ground-dwelling, leaf-litter and lower-canopy utilising invertebrates following the application of a prescribed fire and to investigate their general recovery outcomes through the quantification of invertebrate assemblages at sites of varying time-since-fire (TSF) history and burn status (burnt vs. unburnt). This study was able to identify 7170 invertebrates representing 24 Ordinal taxon with Hymenoptera (55.58%), Araneae (21.52%), Collembola (9.34%), Isopoda (2.52%) and Diptera (2.41%) contributing 91.37% of all invertebrates sampled. This study identified four major responses of taxa. Firstly, Hymenoptera were relatively unaffected by fire, with highest abundances measured immediately following prescribed fire likely due to their soil-nesting behaviour which provides protection from fire and radiant heat. Secondly, Orthoptera, Collembola and Acari showed heavily reduced abundances at recently burnt sites, with a recovery spike observed within 3 years followed by population declines at 5+ years TSF. Despite non-significance for the Orthoptera, this trend is likely indicative of a successional response with these Orders showing a strong preference for an optimal post-fire habitat stage. Thirdly, Hemiptera, Isopoda, Coleoptera, Blattodea, Lepidopteran larvae and the Araneae all showed reduced abundances immediately following fire with increasing recovery observed from 3 years onwards. Finally, the Diptera and Amphipoda showed no distinct fire-related trends. This is likely due to high variability in abundances at sites coupled with overall low detection rates as a result of a lack of litter and reduced moisture content of soils. Overall, this thesis provides evidence for short-term fire effects (<1 month and <3 years) across a variety of invertebrate Orders, longer-term recovery trajectories (>5 years), successional responses of some taxa and highlights the importance of using fire practices that generate habitat mosaics with varying successional stages of vegetative regrowth to facilitate the short-term survival and longer-term persistence of invertebrates in response to prescribed fires.

Michi Sano (UNSW December 2022):

Extreme fire severity drives variation in post-fire recruitment, mediated by seed dormancy type and seed size. Supervisors Mark Ooi, Ryan Tangney (both UNSW)

Persistent soil-stored seed banks are a key mechanism for plant species recovery in fire-prone environments. However, extreme fire severity may generate soil temperatures beyond thresholds seeds are adapted to, posing challenges for predicting the persistence and assemblage of ecosystems. We examined recruitment patterns across a landscape-scale gradient of fire severity, to determine how seed mass and dormancy class may mediate shifts in community assemblages. We posit that extreme fires generate spatially homogenous and particularly high soil temperatures, surpassing lethal thresholds of seeds, which reduces post-fire recruitment and disproportionately impacts smaller-seeded species due to their lack of ability to emerge from greater depth. We surveyed 25 sites in wet sclerophyll (mesic) forests in south-eastern Australia impacted by the 2019-2020 megafires, burnt at either moderate, high, or extreme severity. At each site, two plots measuring $25m^2$ each were installed, and within each plot we counted the number of seedlings. We calculated abundance and density of seedlings from 27 common native shrub species. The relationships between burn severity, dormancy type and seed size, and the dependent variable seedling density, were analysed. Extreme severity fires caused significant declines in seedling recruitment. Recruitment patterns differed between dormancy class, with steeper declines in seedling emergence for species with physiologically dormant (PD) compared to physically dormant (PY) seeds at extreme fire severity. Relative emergence proportions highlighted a hump-shaped relationship between fire severity and small-seeded PY species, and the inverse for large-seeded PY species. Monotonic declines were found for small- and large-seeded PD species.

Synthesis While studies have highlighted how temperature and fire severity can impact seed size/emergence relationships, none have tested how this relationship shapes post-fire community assembly or quantified the importance of seed traits for predicting potential change. Future large-scale extreme severity fires may favour larger-seeded species, shifting community composition and placing smaller-seeded species at risk.

References

Auld, T. D., Keith, D. A., Gallagher, R. V. Tozer, M. G., Ooi, M. K. J., Le Breton, T., Allen, S., Yates, C., van Leeuwen, S., Williams, R. J and Mackenzie, B. D. E. (2022). Frameworks for identifying priority plants and ecosystems most impacted by major fires. Turner Review No. 27. Australian Journal of Botany 70, 455–493

Bradstock, R. A. & Kenny, B. J. (2003). An application of plant functional traits to fire management in a conservation reserve in south-eastern Australia. *Journal of Vegetation Science* 14, 345–354.

Collette, J.C. Ooi, M.K.J. (2021a) Distribution of seed dormancy classes across a fire-prone continent: effects of rainfall seasonality and temperature. Annals of Botany, 127, 613-620

Collette, J.C. Ooi, M.K.J. (2021b) Investigation of 18 physiologically dormant Australian native species: germination response, environmental correlations and the implications for conservation. Seed Science Research 31, 30-38

DAWE (2022). *Fire regimes that cause declines in biodiversity*. Advice to the Minister for Environment from the Threatened Species Scientific Committee on listing of a Key Threatening Process under the *Environment Protection and Biodiversity Conservation Act 1999*. Department of Agriculture, Water and Environment, Australian Government, Canberra.

Enright, N.J., Fontaine, J.B., Bowman, D.M., Bradstock, R.A. & Williams, R.J. 2015. Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. Frontiers in Ecology and the Environment 13, 265-272.

Fairman, T.A., Nitschke, C.R. & Bennett, L.T. 2016. Too much, too soon? A review of the effects of increasing wildfire frequency on tree mortality and regeneration in temperate eucalypt forests. International Journal of Wildland Fire 25, 831-848.

Ferrer-Paris, J. R. & Keith, D. A. (2022). *Fire Ecology Traits for Plants: A database for fire research and management. Version 1.00*. Centre for Ecosystem Science, University of New South Wales, Sydney, Australia.

Gill, A. M. (1975). Fire and the Australian flora. *Australian Forestry*, 38, 4–25.

Gill, A.M. & Bradstock, R.A. (1992). A national register for the fire responses of plant species. *Cunninghamia* 2, 653-660.

Keith, D. A. (1996). Fire-driven extinction of plant populations: a synthesis of theory and review of evidence from Australian vegetation. *Proceedings of the Linnean Society of New South Wales* 116, 37-78.

Keith, D. A. (2012). Functional traits: their roles in understanding and predicting biotic responses to fire regimes from individuals to landscapes. In R. J. Williams, R. A. Bradstock, & A. M. Gill (Eds.), *Flammable Australia: Fire regimes, biodiversity and ecosystems in a changing world* (pp. 120–154). CSIRO Publishing.

Keith, D. A., Williams, J. E. & Woinarski, J. C. W. (2002). Biodiversity conservation–principles and approaches for fire management. In *Flammable Australia: The Fire Regimes and Biodiversity of a Continent* (pp. 401–425). Cambridge University Press.

Le Breton, T.D., Lyons, M.B., Nolan, R.H., Penman, T., Williamson, G.J., Ooi, M.K.J. (2022) Megafire-induced interval squeeze threatens vegetation at landscape scales. Frontiers in Ecology and the Environment 20, 327-334. doi: 10.1002/fee.2482

Le Breton, T.D., Natale, S., French, K., Gooden, B., Ooi, M.K.J. (2020) Fire-adapted traits of threatened shrub species in riparian refugia: implications for fire regime management. Plant Ecology 221, 69-81

Mackenzie, B. D. E., Auld, T. D., Keith, D. A. and Ooi, M. K. J. (2021). Fire seasonality, seasonal temperature cues, dormancy cycling, and moisture availability mediate post-fire germination of species with physiological dormancy. Frontiers in Plant Science 12, 795711

Noble, I. R. & Slatyer, R. O. (1980). The Use of Vital Attributes to predict successional changes in plant communities subject to recurrent disturbances. *Vegetatio* 43, 5-21.

Nolan, RH, Collins, L., Leigh, A., Ooi, M.K.J., Curran, T.J., Fairman, T.A., Resco de Rios, V., Bradstock, R.A. (2021) Limits to post-fire vegetation recovery under climate change. Plant Cell & Environment 44, 3471-3489

Ooi, M.K.J., Tangney, R., Auld, T.D. (2022) Fire and regeneration from seeds in a warming world, with emphasis on Australia. In: Plant Regeneration From Seeds (eds C.C. Baskin, J.M. Baskin). Academic Press, pp. 229-242.

Ooi, M.K.J. (2019) The importance of fire season when managing threatened plant species: A long-term case-study of a rare Leucopogon species (Ericaceae). Journal of Environmental Management 236, 17-24

Ooi M.K.J., Denham A.J., Santana V.M., Auld T.D. (2014) Temperature thresholds of physically dormant seeds and plant functional response to fire: variation among species and relative impact of climate change. Ecology and Evolution 4, 656-671.

Ooi M.K.J. (2007) Dormancy classification and potential dormancy-breaking cues for shrub species from fire-prone south-eastern Australia. In: Seeds: Biology, Development and Ecology (eds S.W. Adkins, S. Ashmore and S.C. Navie), pp. 205-216. CAB International, Wallingford.

Palmer H., Denham A.J., Ooi M.K.J. (2018) Fire severity drives variation in post-fire recruitment and residual seed bank size of Acacia species. Plant Ecology 219, 527-537.

Paroissien, R., Ooi, M.K.J. (2021) Effects of fire season on the reproductive success of the post-fire flowerer Doryanthes excelsa. Environmental and Experimental Botany 192, 104634

Tangney R., Paroissien R., Le Breton T.D., Thomsen A., Doyle C.A.T., Ondik M., Miller R.G., Miller B.P., Ooi M.K.J. (2022) Success of post-fire plant recovery strategies varies with shifting fire seasonality. Communications Earth & Environment 3, 1-9.

Thomsen, A.M., Ooi, M.K.J. (2022) Shifting season of fire and its interaction with fire severity: impacts on reproductive effort in resprouting plants. Ecology and Evolution 12 (3), e8717

Work Package 5. Exploring the wellbeing benefits from engaging in cultural burning

Figure 5.1 . Word cloud of most common words used by respondents in the interviews of Aboriginal practitioners of cultural burning.

UNIVERSITY OF WOLLONGONG

SEALS
School of Earth, Atmospheric & Life Sciences

Research team

Work was conducted by Chief Investigator Dr Katharine Haynes, supported by PhD candidate Vanessa Cavenagh. Kat collaborated extensively with Noel Webster to conduct interviews and produce the main work package output, the Blak Paper. Kat and Vanessa also led two UoW Global Challenge projects collaborating with UoW researchers Lisa Slater, Rebecca Stanley and Yasmine Probst, and external partners DPIE, Ullaladulla Local Aboriginal Land Council, Mudjingaalbaraga Firesticks (Noel Webster) and the Firesticks Alliance Indigenous Corporation. Kat also collaborated with Oliver Costello from Jagun Alliance Aboriginal

Corporation and academics Tim Neale, Tasmin Dilworth and Tony Jones on the Bushfire and Natural Hazards CRC. These are the more prominent examples of the many relationships developed with First Nations groups.

Overview

The aim was to explore the wellbeing benefits of cultural land management practices, particularly cultural burning and to identify ways to better support First Nations peoples to fulfil their aspirations to care for Country. The project suffered delays because of difficulties in recruiting First Nations researchers and from COVID-19. The core of the project was the conduct of 11 interviews with Aboriginal cultural burning practitioners, a body of work that eventually contributed to the Blak Paper (see outcomes below).

Aims

- Build relationships and trust with Indigenous communities
- Co-design research studies
- Document lived experiences of engaging in cultural land management
- Collect meaningful in-depth qualitative data
- Define wellbeing outcomes collaboratively
- Develop wellbeing indicators collaboratively
- Design and test wellbeing indicators
- Document cultural burning diversity
- Complete narratives of cultural burning

Projects and outcomes

The overarching aim of this work package was to explore the wellbeing benefits of cultural land management practices, particularly cultural burning and to identify ways to better support First Nations peoples to fulfil their aspirations to care for Country. It builds on previous research that measured direct benefits for Aboriginal health and well-being by caring for Country in the Northern Territory. While that study considered re-engaging with Country in a broad sense, and analysed health markers such as BMI, blood pressure and type 2 diabetes status, the current project focused on cultural burning in a social research context, consulting with Indigenous communities through in-depth qualitative research methods to explore and document their perspectives.

This work package made strides in these directions beginning with an exploration of current cultural burning practices, delivering numerous well received events and publications including a highly successful workshop for Aboriginal teenagers on the South Coast. It concluded with strong recommendations for future development.

Delay to project start and impact of Covid-19 to WP5

The original intention for WP5 was for it to be led by a First Nations researcher, however, following two unsuccessful targeted recruitment drives a non-First Nations researcher was eventually hired in a third open interview process. Research on WP5 therefore began in June 2019, well after the other packages of research. A successful human research ethics application was reviewed and granted by UOW in October 2019 and a process of networking, interviewing and relationship building began. However, this was significantly curtailed by the impacts of COVID-19 from March 2020 onwards which impacted the research throughout. Dr Haynes left UOW in November 2021 to take employment with Natural Hazards Research Australia. The intention was to replace Dr Haynes with a First Nations researcher to finalise the WP and to test the tools developed to measure long-term changes in wellbeing. However, this process was delayed and eventually unsuccessful as UOW removed the funding from the position.

Co-development

The team's approach was highly collaborative with First Nations community members and agency staff involved in a process of co-development at every stage.

- Improved understanding of lived experience of cultural burning.
- Improved understanding of the need to centre "Culture" and connection to country in land management.
- Improved understanding of the challenges to expanding cultural burning.
- A survey tool to assess how cultural burning practice changes practitioner's wellbeing.
- Youth-Led Cultural Burning for Resilience (Ulladulla June 2021) and associated mini-documentary.
- Listen, because Country is speaking (the Blak Paper, chief author Noel Webster). This collaboration between WP5 and the Cultural Fire Management Unit of DCCEW was used to inform the strategies of that unit.
- Three Honours student theses, one on the effects of cultural burning in obligate seeding shrub species dynamics, one on the minimum inter-fire intervals experienced by obligate seeding shrubs, and one comparing soil impacts of cultural burns and Hazard Reduction burns.
- Contributions to the report Cultural Land Management in Southeast Australia Project: project report "Developing the foundation for an Indigenous-led and co-designed research program for land management with Traditional Owners" , Authors

O Costello, T Dilworth, K Haynes, T Jansen, T Neale, funded by Natural Hazards Research Australia, Melbourne.

- WP5 recommended a range of funding, governance and cultural changes to support the expansion of cultural burning.

Lived experience

To understand the social benefits of cultural burning the team interviewed 11 active Aboriginal cultural burning practitioners in NSW. Interviews were loosely semi-structured and in-depth. They were conducted outside on Country, at a location of cultural significance to the participant. The aim was to centre Country in the conversation and for the process to be informal and a process of story-telling and yarning. While there were topics to discuss, the conversation flowed and was directed by the participant. Participants were simply asked to reflect on their journey of connecting to Country, for some this had been an ongoing process supported by family and community since their birth. For others, it was a life changing journey of discovery.

On using cultural burning as a pathway to connecting to Country:

We are learning our true identity, if puts nothing but pride in us and makes us stand strong because we are finally getting to learn who we are and what we are about … it's crazy how much just a bit of fire can do for people and that's not just for us; that's for each tree and animal too.

Ado Webster, Mudjingaarbaraga Firesticks

Yeah, that sparks an interest in culture for the young people and once they get that little bit of interest going and looking at their culture, and burning does that to them. I've seen a couple of young fellas just change straight away because they're into their burning – now they're into tool making and everything.

Uncle Les Simon, Batemans Bay LALC Walbanga Elder

Centring "Culture" in land management

Participants emphasised the holistic benefits of cultural land management for Country: that it concerns all living things, landscapes, elements and the connections between them. They pointed out that hazard reduction burns follow a uniform methodology to reduce risk, whereas cultural burns are sensitive to environmental and cultural needs, responding to when is the right time for Country, not for people. Since caring for Country involves connecting with families and communities, it is seen as a reciprocal and spiritual relationship.

Connection to Country

Overwhelmingly, respondents all discussed how cultural burning is a journey of healing people and the environment and is an extremely valuable pathway for connecting people back to Country. They agreed that engagement with cultural burning and connection to Country has significant benefits for spiritual, physical and mental health, increasing pride, confidence and resilience to life's knocks and stresses. Many expressed frustration and grief from the impacts of the 2019 / 2020 fires.

Challenges for cultural burning

Practitioners spoke of numerous challenges from a power imbalance and the pressure to compromise, to practical issues of training and funding. In particular, concerns were raised about the need to compromise culturally to conduct burns in order to comply with fire and land management agency policy. Some saw a danger of cultural burning being manipulated to suit other needs, such as to get more area burnt and to reduce fuel. There was a general concern about the role of Aboriginal people in cultural burning: that it must be Aboriginal led and conducted, with good cultural frameworks and protocols. It was also noted that there is limited Aboriginal representation within agencies and on decision-making bodies.

Survey tool to measure long-term changes in wellbeing

From the analysis of the in-depth qualitative interviews the team designed a survey tool that can be used to measure long term changes in wellbeing. However, in order to measure a longitudinal trend, there needs to be data to measure, and First Nations people need to be involved in ongoing care of Country through culturally based activities. Currently, engagement is typically through one off, or limited projects and cultural burns. No long-term changes can therefore be measured until there is ongoing support and legislation that enables and fosters sustainable First Nations led cultural land management.

The survey consisted of two sets of questions, one to measure baseline wellbeing data before engaging in cultural activities and a second set that can be used after an event, or preferably, one that can be used many times to measure longitudinal change in wellbeing from ongoing engagement with on-Country activities. The questions ask about connection to Country, happiness and spiritual / mental health. For example: 'My health is connected to Country. If Country is sick I am sick'; 'Challenges of life have disconnected me from my mob.' 'I rate my spiritual health as high'. As noted above, the questions were based on the in-depth interview data, and used the vernacular that respondents had used to describe what it felt like to be disconnected from Country and their experience of re-engagement.

The aim for the survey is to collect data that demonstrates the considerable benefits to First Nations and non-First Nations peoples of engaging with on-Country culturally centred land management activities. It is hoped that this data can then inform policy and practice to better support Aboriginal-led cultural land management.

Conclusions

A way forward

The work undertaken under WP5 gave voice to numerous Aboriginal youth and elders and is an important step in disseminating and acting upon their perspectives.

End users of information gathered during the work package include a number of non-government organisations including, WP5 working group members from the Firesticks Alliance, Mudjingaarbaraga Firesticks, Mullumbimby Firesticks, Ulladulla Local Aboriginal Land Council and a range of Indigenous communities and youth. Government organisations directly involved include, DCCEW, NPWS, and the Cultural Fire Management Unit within DCCEW, as well as RFS. Other broader end users are Natural Hazards Research Australia and the Blue Mountains World Heritage institute.

Issues remaining

While advances in understanding the significant wellbeing benefits have been made through this work package, many frustrations remain that significantly erode wellbeing. One of the obstacles to supporting and promoting cultural land management, however, is that many organisations do not really understand what is meant by ensuring that culture is centred within the process and that it is Aboriginal led and owned. Many First Nations people feel they are not supported, taken seriously or properly funded. That they continue to be ignored and are not allowed to voice their views and experiences. The experiences of colonisation, racism and an imbalance of power remain. These structural barriers restrict access to Country, the repatriation of knowledge and the building of any real capacity and long-term change.

Recommendations

Researchers and their collaborators propose changes to funding, policy and relationships between Aboriginal communities and other fire and land managers. In particular they suggest the following:

- Provide long term funding and policy change to support Indigenous-led cultural land management, through:

- Greater opportunities for cultural land management training and the repatriation of cultural knowledge
- Ensuring Indigenous cultural knowledge is recognised, and more equitable power relationships are created across fire and land management
- Creating and supporting sustainable livelihood opportunities for cultural land management practitioners to conduct burns governed by strong cultural protocols.

In order for this to be achieved, governance must change to support Indigenous people's right to care for Country their own way. Ongoing funding must be provided, and Community-led initiatives must be prioritised (decentralised, bottom-up).

Key Outputs

In addition to the central aim of documenting the lived experiences of First Nations people in NSW to explore the wellbeing benefits of engaging with CLM practices, the project also supported a number of important projects and outputs. These include:

Youth-Led Cultural Burning for Resilience, Ulladulla June 2021.

This two-day workshop for Indigenous youth was an Aboriginal-led community project supported by the Ulladulla Local Aboriginal Land Council, the NSW Bushfire Risk Management Research Hub, the University of Wollongong's Global Challenges program and the environment organisation, Treading Lightly Inc. and Mane Collective Video Production.

Local elders mentored emerging leaders who facilitated the workshop. The emerging leaders in turn mentored 24 Aboriginal teenagers, aged between 14 and 17, who attended the workshop. Participants were invited from four NSW South Coast schools - Batemans Bay, Nowra, Ulladulla and Bomaderry.

The workshop emphasised cultural renewal, while giving students the opportunity to participate in a cultural burn. In this way it was seen to explore the power of an immersive experience to increase cultural connection and wellbeing in Aboriginal youth. Research data was collected through participant observation and a series of semi-structured interviews before, during and in the weeks following the workshop. A number of these interviews were captured as digital stories on video camera.

The majority of the students had never done a cultural burn before and many found it very beneficial, particularly as an important insight into Aboriginal culture and building identity.

Some talked of how they felt disconnected from their culture, wanted to know more about it and felt the workshop had really helped and inspired them to begin a journey of reconnection, confidence and pride. Overall, the project leaders found that cultural burning provided a clear pathway for Aboriginal youth to connect with culture and Country.

A number of clear outcomes were identified through the action orientated research: 1) That hands on cultural learning played an important role in empowering and engendering resilience in Aboriginal youth; 2) the mentoring of emerging leaders and young participants builds capacity and confidence; 3) the development of a youth-led transformative learning process. 4) collection of digital stories and the documentary film that continue to be viewed by audiences in Australia and internationally increasing non-Indigenous peoples' understanding of Indigenous ways of connecting to culture and Country.

The film from the workshop, *Cultural Burning for Resilience, The Mini-Documentary,* that captures digital stories from the youth involved, was created by Mane Collective Video Production and the research team as part of the interactive participatory research process. The film is part of an exhibition hosted by the Australian Museum, Sydney and promoted through a number of screening workshops, webinars and social media. In addition, information from the workshop was used as a case study example in the 2022 State of the Environment Report.

Links to documentary on Youth-Led Cultural Burning for Resilience workshops:

Short version: https://vimeo.com/716285434/a562d67538

Long version: Cultural Burning for Resilience | The Mini-Documentary on Vimeo

LISTEN, BECAUSE COUNTRY IS SPEAKING: Conversations on, with and for Country with key Aboriginal cultural land management stakeholders from across NSW (Blak Paper)

This project was a collaboration between the WP5 research lead and staff from the Cultural Fire Management Unit, DCCEW. The aim for this work was to ensure the views of key First Nations stakeholders were included in the establishment of the new cultural fire management unit within DCCEW. Thirteen key First Nations cultural burning practitioners / key stakeholders were interviewed. The interviews were semi-structured and centred Country. They are best described as yarning.

The conversation was framed around participants' views of: current governance arrangements, policies and structures for cultural burning; the role of the Cultural Fire Management Unit and the NSW government in general; current land management practices;

and the changes that are needed to support community-led cultural land management. This project was an important process of meaningful community outreach and an opportunity for strengthening relationships.

The Bushfire HUB evaluation report stated that this work :

"..is considered by some to be a significant achievement by WP5. The report is the first of its kind document that details the views of key cultural burning practitioners and the impacts of the 2019/20 Black Summer Bushfires on Indigenous communities, which was noted to be a high priority knowledge gap for NPWS and RFS"

The Blak paper remains under embargo at DCCEW while some sensitivities are negotiated. It is anticipated that the report will be published in the second half of 2023.

Additional outcomes

Madeleine Selvey Honours thesis (October 2019):

The effects of Contemporary and Cultural prescribed burning on post-fire above- and below-ground shrub dynamics. Supervisor Owen Price

Reinstating Australian Aboriginal burning regimes (Cultural burning) is often advocated as an alternative to Contemporary prescribed burning practices. However, there is a scarcity of published knowledge regarding the influence of this prescription of fire on biota, particularly shrub below- and above-ground dynamics, in the sclerophyll forests of South Eastern Australia. This study sought to assess the comparative effects of Cultural and Contemporary prescribed burns and their associated fire severity on shrub mortality and the breaking of fire dependent physical dormancy and subsequent germination of five common Australian shrub species (*Aotus ericoides, Acacia longifolia, Bossiaea heterophylla, Bossiaea stephensonii,* and *Pultenaea linophylla*) on the south coast of NSW, Australia. Binomial generalised linear models indicated that shrub mortality was significantly greater in the Cultural burns than the Contemporary burns. Furthermore, in the Cultural burns there was a significant positive relationship between mortality and shrub size (stem diameter). The severity of both the fires was low; however, fire severity was greater in the Contemporary burns than in the Cultural burns. In the Cultural burns, temperatures below-ground did not reach thresholds high enough to trigger germination in any of the selected species, while the Contemporary prescribed burns reached temperatures that were able to break the dormancy of a proportion of all species studied. Variation in the mortality and germination rates of shrubs detected between the two prescriptive fire types has important implications for the biodiversity management of the areas in which these fires occur. In the Cultural burns the mortality of obligate seeders was high, but the fire did not reach the temperatures below-ground to break seed dormancy, suggesting that the potential recruitment of these species may be significantly lowered. The Contemporary prescribed burns, while low in severity, still produced below ground temperatures high enough to break the dormancy of both and high and low threshold species. This implies that obligate seeder shrubs subjected to the Contemporary prescribed burning regime will be able to maintain their persistence over time and if Cultural burning was the only fire regime to occur there could be profound reductions in the species composition and diversity of the area over time. Whether these outcomes are ideal depend on the initial management objective.

Milo Morrison-Jones Honours thesis (October 2021):

Why the insensitivity? Plant species across New South Wales tolerating short fire intervals. Supervisor Owen Price

Fire as a global disturbance has acted across millions of years to shape terrestrial biomes. It has shaped the evolution of plants in concert with other disturbances and shape flora as we know it today. Increased global fire activity has posed the question to managers of how best to manipulate fire regimes to benefit people and biodiversity. Cultural burning is a form of prescribed burning undertaken by Indigenous people for a variety of reasons (often frequently at low intensities) promoting the regenerative aspects of fire. The frequency at which this is applied can be at odds with fire interval-based 'thresholds' developed by scientists, such as those generated based on plant life history traits for New South Wales (NSW), Australia. Using combinations of critical plant traits (plant functional types), predictions about future vegetation change are made possible.This study sought to explore whether the shortest fire intervals (minimum intervals) experienced in past observations of fire sensitive plant species affected their survival. Five prevalent fire-prone vegetation formations were chosen in which to test minimum intervals against the primary juvenile periods of fire sensitive (obligate seeding) species. Other factors (role of sample size, fire type and systematic differences in plant functional types) were also explored. The overall results are very strong in suggesting that minimum intervals in the past do not affect the subsequent survival of fire sensitive plant species in NSW. This is unexpected when considering their life history traits and the information given in the NSW Flora Fire Response Database. The most likely explanation is the fire patchiness within fire perimeters enabling adult plants to survive. Other likely explanations include variation in life history traits (such as resprouting response and juvenile period) and seedbank longevity. The insensitivity of these 'vulnerable' plants to landscape scale fire intervals as used in NSW fire management is called into question, and it is likely that concerns about the effects of high fire frequency on flora are overestimated to some degree. The increasing calls for Cultural burning to light landscapes again may not have as detrimental effect on plant populations if they are patchy. Managers are implored to rigorously test old assumptions and new fire management paradigms.

Jessica Drinnan Honours thesis on Soil Health

Jointly supervised with Prof Dosseto

The project explored the soil characteristics at three sites on a block of land under the custodianship of the Ulladulla local Aboriginal Land Council. A comparison of the soil was made between sites following a prescribed burn conducted by the RFS, a cultural burn and a control site that had not been burnt. The study identified significantly improved soil health at the site that had been culturally burnt compared to the other two. The abstract is shown below.

Sustaining soil health is necessary for supporting the structure and functioning of aboveground ecosystems (Neary *et al.* 1999). When exposed to fire, the soil's physical, chemical, and biological constituents considered essential for these processes are susceptible to a range of functional changes. In southeast Australia, Traditional Custodians have utilised fire as a land management tool for thousands of years, with the purpose of protecting and enhancing the health and biodiversity of the landscape (Firesticks Alliance Indigenous Corporation 2022). Although the impact of bushfires and prescribed burns on soil properties is understood, little is known about the effect of cultural burning. Through a range of field- and laboratory-based experiments on NSW's south coast, this study has shown Indigenous-led fire practices improves soil health, when contrasted with a government organised "cool" burn. The cultural burn's low severity caused minimal volatilisation to soil organic matter, allowing for additional inputs to existing nutrient pools, this resulted in >1.5 times more carbon and nitrogen. Through this incorporation, bulk density and moisture content were enhanced, which are trends directly linked to improved soil functionality (Al-Shammary *et al.* 2018). Additionally, soil pH remained within the regions naturally occurring range (5.1-5.5), while salinity was found to be >57% lower. Although no differences in biological activity were observed, the culturally burnt environment is expected to benefit from improvements to the soil's physiochemical parameters. Furthermore, this research demonstrates the benefit of cultural burn practices applied to Country for belowground ecosystems, in a region left largely untouched from Traditional Land Management for decades.

Work Package 6: Optimization of cost-effective fire management to balance multiple objectives

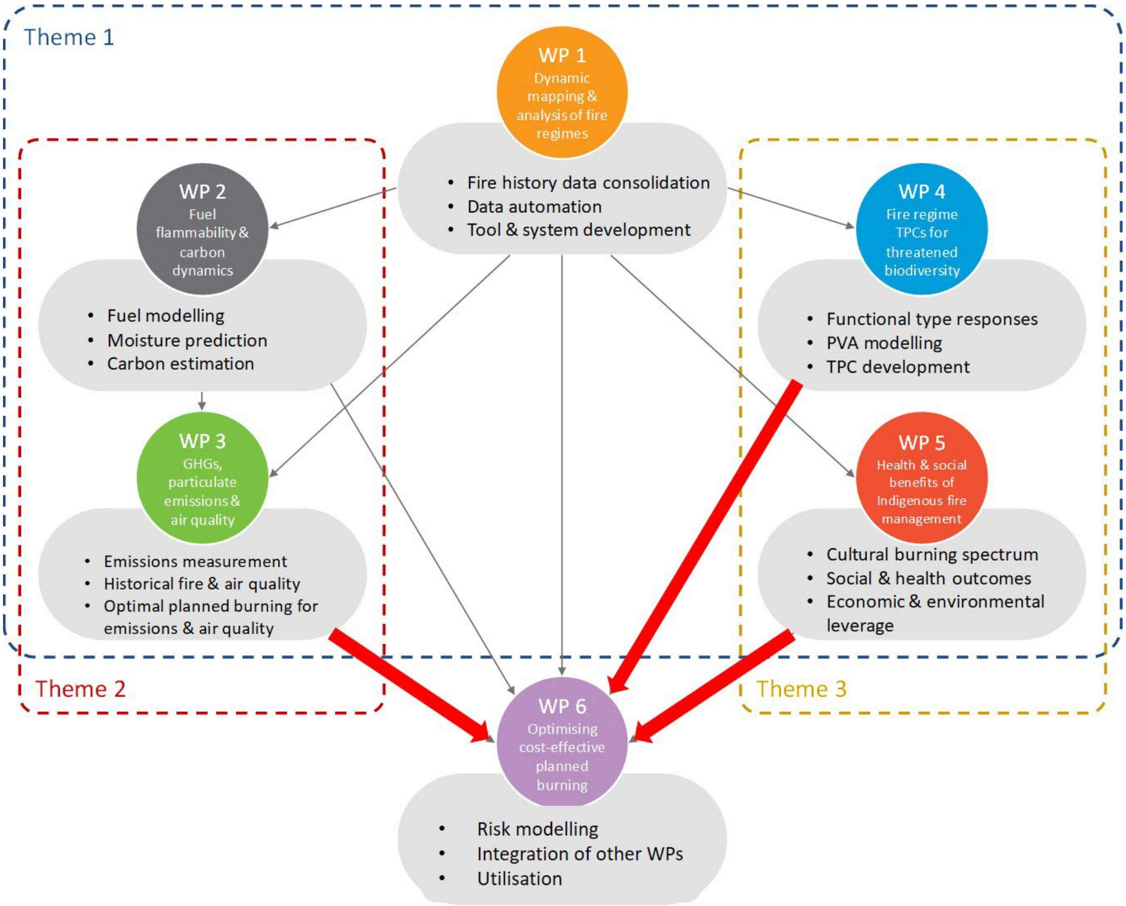


Figure 6.1 Connections between Hub Work Packages. Note that while all WPs flow into WP6, WP6 has a special role of integrating specific outputs from WP3, WP4 and WP5. Adapted from original Hub proposal.

Research team

The chief investigator was Dr Hamish Clarke from the University of Wollongong. Smoke health cost research was led by Dr Nicolas Borchers Arriagada at the University of Tasmania. Risk modelling was carried out by Dr Clarke, Brett Cirulis and Professor Trent Penman, from the University of Melbourne. All phases of the project were developed and overseen by Dr Clarke, Professor Penman, Associate Professor Owen Price and Senior Professor Ross Bradstock from the University of Wollongong. Inputs from other Work Packages were led by Associate Professor Price and Michael Storey (WP3; University of Wollongong), Associate Professor Mark Ooi (WP4; UNSW) and Katharine Haynes (WP5; University of Wollongong). WP6 researchers and Michael Bedward (UOW) conducted research for NSW DCCEW on

prioritisation of burn blocks and prediction of prescribed burning coverage. Research reports available on request.

WP6 researchers are grateful to the end user group that met regularly to discuss and provide feedback on progress, as well as a broader group of staff who we interacted with via emails, meetings, phone calls, Bushfire Hub conferences and webinars to discuss the project, evaluation of the Enhanced Bushfire Management Project and related issues. NSW Rural Fire Service: Melissa O'Halloran, Laurence McCoy, Katie Collins. NSW National Parks and Wildlife Service, NSW Department of Planning and Environment: Felipe Aires, Don McDonald, Patrick Schell, Breanna Downton, Phoebe Bayerlein, Rachel Hannan, David Taylor. NSW Department of Planning and Environment: Matthew Adams, Greg Summerell, Tom Barrett, Nadia Kanhoush, Robert Carr, Jasper Odgers

Summary

Work Package 6 (WP6) focused on the Optimisation of cost-effective prescribed burning to balance multiple objectives. This is because while fire management can change fire regimes, the overwhelming challenge is to provide the optimal balance between the mitigation of risks to life, health and property and other key environmental values (e.g. carbon, biodiversity).

In order to estimate the risk mitigation available from different prescribed burning strategies, we conducted a large number of fire behaviour simulations in thirteen case study landscapes in NSW under different fuel treatment, weather and ignition scenarios. Using Bayesian Decision Networks, we then estimated the annualised risk of area burnt by wildfire, life loss, house loss, infrastructure damage and environmental impact, under each of these fuel treatment scenarios. Where possible, we assigned costs to these outcomes, as well as to the cost of fuel treatment, to estimate the cost-effectiveness of different strategies. We also investigated the effect of climate change on risk, via fire weather effects on ignition probability and fire behaviour. This risk modelling framework facilitated individual landscape-level analyses as well as comparisons between landscapes.

Key messages

1. Prescribed burning is not a silver bullet. It can mitigate, but not eliminate, a range of bushfire-related risks. There is no one size fits all solution to prescribed burning. We

need to develop solutions tailored to local conditions. The effectiveness of prescribed burning at changing bushfire behaviour is influenced by many factors such as weather, fuel moisture, drought, vegetation type, topography, time since the prescribed burn, and how much fuel was removed or modified by the original prescribed burn.

2. We need to understand - and if possible quantify – the effects of both bushfire and fire management on the risks to all the things we care about ('values'). Values include loss of life and property, greenhouse gas emissions and smoke, health impacts of smoke, water quality and other ecosystem services, vegetation condition including the persistence of threatened species and communities, and of fire-tolerant and fire-sensitive species, pests and weeds, impacts on infrastructure, agriculture, tourism, community wellbeing, recreation, Aboriginal cultural heritage and European cultural heritage.
3. Under extreme weather conditions, prescribed burning may have little or no effect on fire behaviour. Climate change is increasing the frequency of extreme weather conditions and thereby undermining prescribed burning effectiveness.
4. We need to understand – and where possible quantify – the costs associated with the effects of both bushfire and fire on the risks to our vaues.
5. We need to develop a respectful, equitable and evidence-based relationship between Aboriginal cultural burning and the prevailing fire management paradigm.
6. We need risk modelling frameworks that accommodate diverse values, that make trade-offs and uncertainty transparent, that can be tested and updated, and that fire managers can work with.

Aims

To integrate results across all WPs to examine trade-off strategies for cost-effective

planned burning that build on past and present knowledge and provide adaptation to human and climatic changes in the future.

Projects and outcomes

WP6 generated a formidable amount of output and summarising it is a challenge. This overview is divided between findings related to risk modelling (risk estimation based on a large number of fire behaviour simulations), and findings related to the integration of values from other work packages of the Hub. A discussion of how best to use the output from WP6 can be found below in “Do's and Don'ts of Using WP6 Output”.

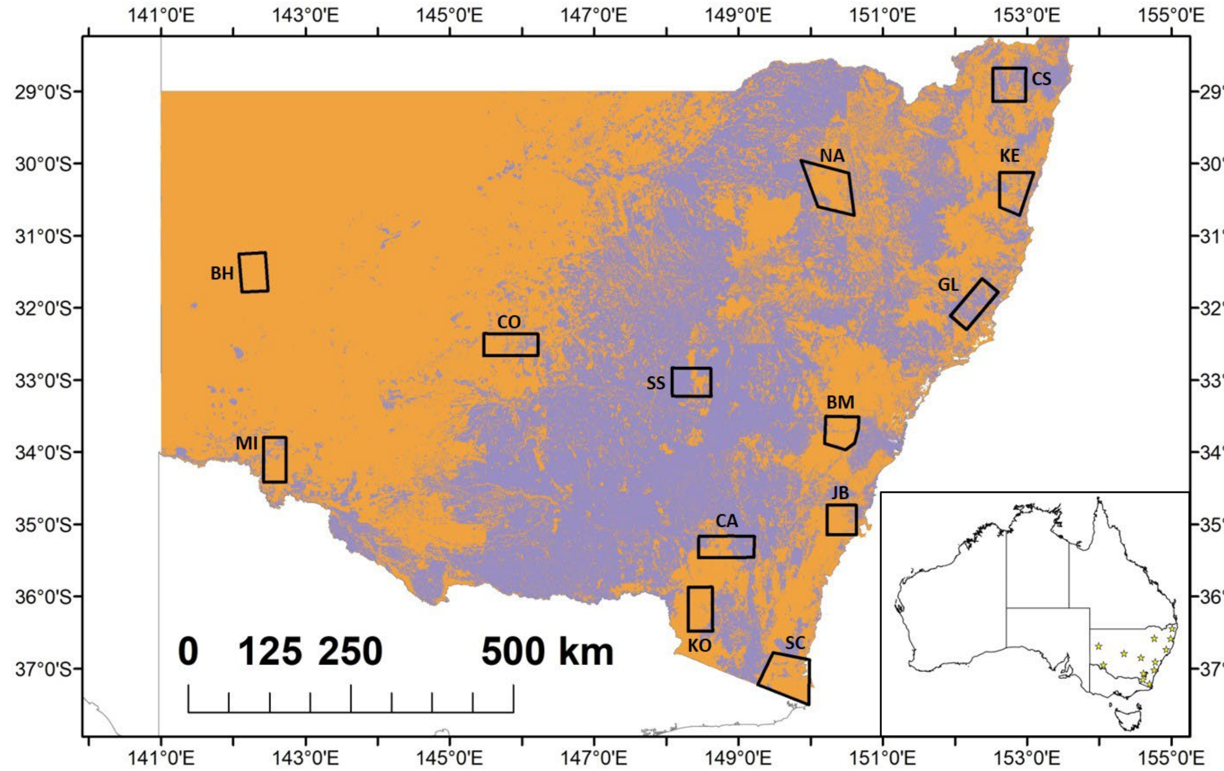


Figure 6.2 Fire behaviour simulations and risk estimation were carried out in 13 case study landscapes: Broken Hill (BH), Mildura (MI), Cobar (CO), Southwestern Slopes (SW), Nandewar (NA), Canberra (CN), Kosciuszko (KO), Casino (CS), Kempsey (KE), Gloucester (GL), Blue Mountains (BM), Jervis Bay (JB), Southeast Corner (SC). Colour shows dominant land cover (orange = native vegetation, purple = cleared or modified vegetation).

Risk modelling

There is no one size fits all solution to prescribed burning. The response of risk to fuel treatment varies by management value and by landscape.

The biggest response of area burnt to fuel treatment was found in the Blue Mountains, Canberra and Gloucester. In these case study landscapes there was a greater than 50% reduction in the residual risk of area burnt by wildfire under the highest fuel treatment rates.

The smallest response of area burnt to fuel treatment was found in Casino, Gloucester, Jervis Bay and Kosciuszko. In these case study landscapes there was a less than 10% reduction in the residual risk of area burnt by wildfire even under the highest rates of fuel treatment. The response of area burnt to fuel treatment was generally weak in arid areas including Cobar, Mildura, Broken Hill and the Southwestern Slopes. However, there were some exceptions where the response was stronger such as area burnt in Broken Hill and area burnt below minimum fire threshold (FT) in the Southwestern Slopes.

The response of life loss, house loss, road damage and powerline damage to fuel treatment was often quite similar to the response of area burnt by wildfire. In some cases where the response was different, it related to a lack of people, homes, roads or powerlines in the given case study landscape. In other cases the reasons were more complex and likely related to the precise formulation of the functions used to model fire impacts on each management value, as well as the configuration of different vegetation and asset types in the landscape.

The response of area burnt below minimum FT to fuel treatment was often complex. In most landscapes an increase in fuel treatment rates was associated with an increased risk of area being burnt below its minimum FT. In the Blue Mountains the opposite relationship held, with the area being burnt below its minimum FT declining with increasing fuel treatment.

The relationship between cost and fuel treatment strategy was complex. Different treatment strategies were associated with different costs to individual management values as well as overall costs for both fuel treatment and bushfire impacts.

The total cost of bushfire impacts was highest (>$6m at upper end) in the Blue Mountains and Gloucester, followed by Jervis Bay, Casino, Canberra and Mildura (~$2.5m at upper end). The lowest costs of bushfire were in Broken Hill, Nandewar, Kosciuszko and Southeast Corner. The total costs are a function of treatment amount and effectiveness, wildfire size and the amount of assets in a particular landscape.

The response of total costs to treatment was greatest in Canberra and the Blue Mountains, areas where there is a strong relationship between prescribed burning and decreased risk of area burnt by wildfire.

Tradeoffs are fundamental to fire management. In many cases as treatment increases, there is a decline in the area burnt by wildfire, life loss, property and infrastructure damage but an increase in environmental impacts. This represents a tradeoff between management values.

While there is a lowest cost solution in the narrow terms defined here, in many cases a relatively small change in total costs is associated with a relatively large change in risk or cost to a specific management value. This represents a tradeoff between cost and management values.

Climate change can lead to substantial increases in risk via weather effects on ignition and fire behaviour. Under best case climate change scenarios, the effectiveness of prescribed burning is expected to remain largely unchanged. Worst case scenarios can be interpreted as requiring an increase the future fuel treatment rate in order to achieve the same effect as current rates. Conversely, worst case scenarios can be thought of as leading to diminished effectiveness in the future if current fuel treatment rates are maintained.

Integration from other work packages

Introducing additional values to the risk modelling framework leads to a more realistic picture of the effects of fire, tradeoffs and the cost-effectiveness of different solutions. By implication, it encourages caution when interpreting current estimates of the risk associated with different fuel treatment strategies, whether they such estimates are produced using our risk modelling framework or other methods.

Initial results suggest that restricting prescribed burning to the time of year when impacts on fire-sensitive vegetation are lowest will not necessarily lead to uniform benefits. That is, incorporating fire seasonality (i.e. the time of the year when vegetation is burnt) into our risk assessment led to complex and non-linear changes in the area burnt below minimum FT. This topic is important and requires further research.

Initial results suggest that wildfire smoke health costs can decrease substantially in landscapes where area burnt by wildfire responds strongly to fuel treatment. However, there are also significant smoke health costs associated with increasing prescribed burning treatment. Incorporating the cost of smoke health impacts led to an increase in overall costs in most cases, including much higher costs in the Blue Mountains, Gloucester and the Southeast Corner, and higher costs in Jervis Bay, Kosciuszko and Canberra. This topic is important and requires further research.

Conclusions

Do’s and Don’ts of Using WP6 Output

- Do take the time to read through the methods and understand what is being modelled and how.
- Do consider relative changes. Relative changes are useful because they come in the currency of residual risk, which refers to the risk relative to a no treatment strategy and can be compared between values and landscapes.
- Do consider absolute changes. It is important to remember that a 10% change in residual risk will mean very different things in landscapes where risk is high, compared to landscapes where risk is low.
- Do look for patterns. The risk modelling allows a number of patterns and comparisons to be explored: edge vs landscape treatment, life and property vs environmental impacts, landscapes with high vs low responsiveness to treatment, smoke health costs, climate change impacts. In some cases these patterns are clear and strong and in other cases there may not be much difference.
- Do talk to us. We may be able to provide easy answers to your questions, comments or concerns. Or they may open the door for us to improve how we do things and deliver new and better risk estimates.
- Do factor in other knowledge and ‘sanity tests’ when interpreting results. We have emphasised an ‘apples with apples’ approach in order to be able to fairly and objectively compare strategies and risk to management values across landscapes, but this means we have not been able to factor in some local information that may influence fire behaviour, risk or costs.
- Do use the results to explore different strategies, test assumptions and generate hypotheses.
- Do use the results as a tool for communicating with colleagues, managers and stakeholders.
- Do use the results as a way of framing the challenge of risk mitigation: how can we understand the effects, costs and benefits of fire and fire management on all the things we value?
- Don’t assume the meaning of specific words. Check the terminology section where we explain what we mean by risk, residual risk, management value and other key terms.
- Don’t assume that models are perfect. We know there are limitations in our understanding of fire behaviour, fire impacts (e.g. the risk of house loss from wildfire, smoke generated by wildfire vs prescribed fire), and costs.

- Don't assume that models are complete. We know there are many factors, impacts and costs yet to be included e.g. pyroconvective events, suppression, firefigher health and safety, ecosystem services etc.
- Don't assume that the strategy with the greatest risk mitigation for a particular value, or the lowest overall cost is the best. Our approach emphasises the need to consider many values and costs and acknowledges that different stakeholders may have different priorities.
- Don't get lost in the detail. There are tens of thousands of fires simulated in every landscape, multiplied by almost 50 treatment strategies, multiple management values, plus costs and climate change impacts. These outputs make most sense when taken in relative terms, and compared to the global picture, rather than interpreted at a very fine scale.

Key Outputs

Bushfire risk mitigation under contemporary management: a case study of potential fuel treatment effectiveness across NSW, se Australia

Ross Bradstock, Michael Bedward, Owen Price, Hamish Clarke, Brett Cirulis, Trent Penman

We applied the WP6 simulation framework to estimate residual risk for the proposed planned burning treatment program from 2016 to 2025, that encompassed NPWS estate in eight of the case-study landscapes. We estimated the median annual treatment rate (% area per annum) in NPWS land overlapping treatment block types (Edge, Landscape) used in pre-existing simulation studies. Corresponding estimates of median residual risk for the range of management values were then derived from pre-existing results of the simulation studies. The proposed annual planned burning program was highly variable both within and between case-study landscapes, resulting in median annual treatment rates ranging from 0 to 15% and 0 to 8% of Edge and Landscape blocks, respectively. Corresponding median residual risk estimates were also highly variable, ranging from 55 to > 95% for lives, property and infrastructure and generally exceeding 100% for TFI, indicating increased risk resulting from planned treatment, except in the Blue Mountains case study. This indicated risk trade-off between lives/property/infrastructure and one key environmental indicator, potentially resulting from current planned burning approaches. There is scope for further decreasing residual risk to lives/property/infrastructure beyond the modest levels estimated here, via increased rates of treatment, particularly if effort is focussed on Edge blocks, close to developments. Understanding trade-offs with other management values, such as smoke and human health, along with evaluation of the relative cost effectiveness of the current, planned burning program will assist in better evaluating future options and directions.

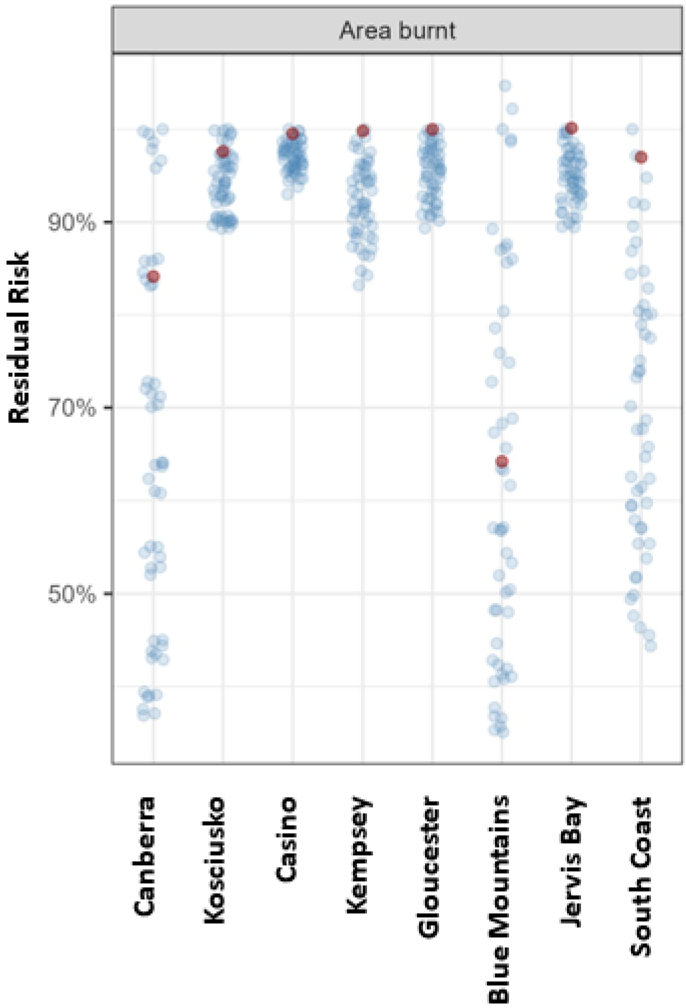


Figure 6.3 Comparative**,** residual risk resulting from the planned NPWS treatment program (2016 to 2025) across the case study landscapes, for area burned by unplanned fires, human (lives, houses, roads, powerlines) and environmental (Tolerable Fire Intervals, TFI) values. Dark red points indicate median estimates for the annual, planned NPWS treatment program. Light shaded points are from the

Borchers-Arriagada, N, Bowman, D, Price, O, Palmer, AJ, Samson, S, Clarke, H, Sepulveda, G, Johnston, FH (2021) Smoke health costs and the calculus for wildfires fuel management: a modelling study. *Lancet Planetary Health* **5**, E608-E619.

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.

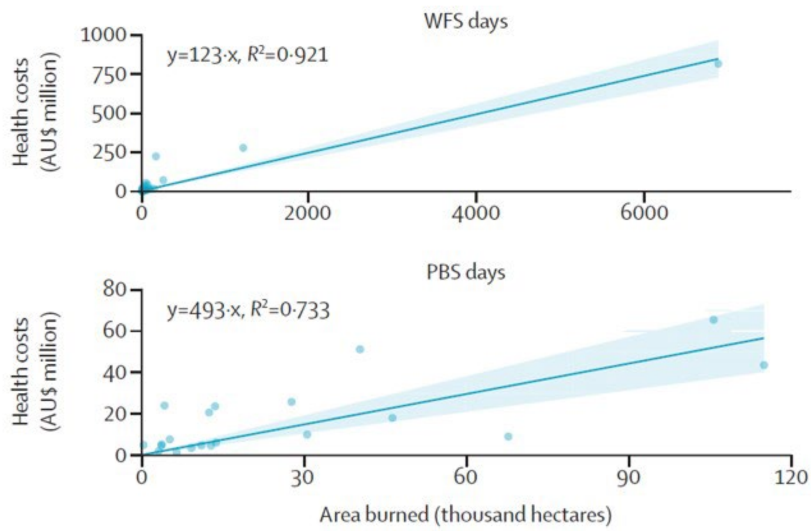


Figure 6.4 Predicted health costs (as a function of population weighted exposure for NSW) for days dominated by Wildfire (WSF days) and by HR (PBS days).

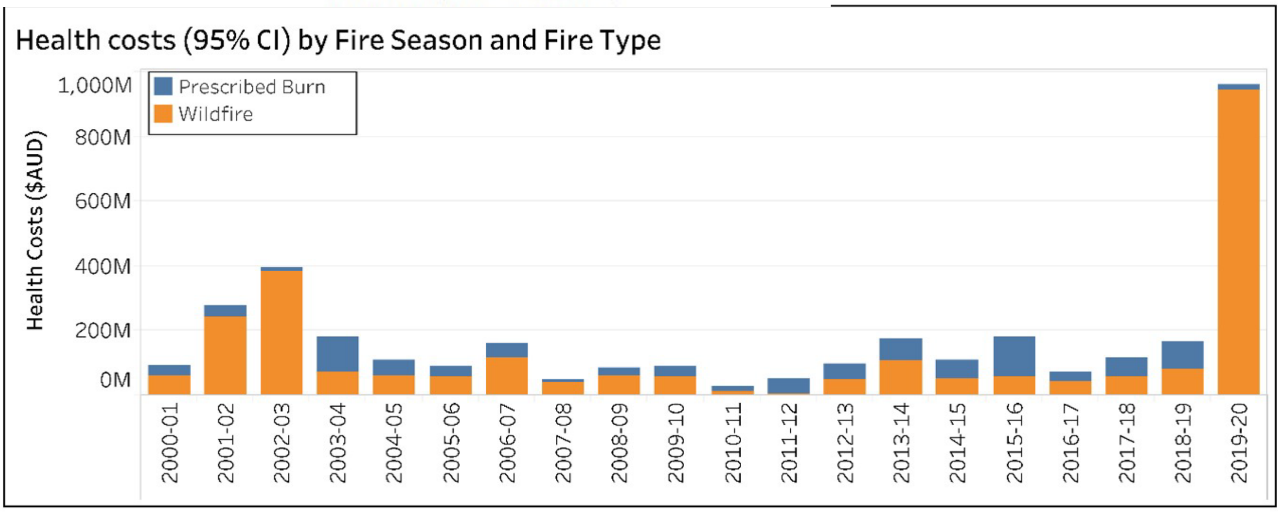


Figure 5 Estimated human health costs of smoke from prescribed fire and wildfire in NSW since 2000.

Clarke, H, Cirulis, B, Borchers-Arriagada, N, Bradstock, R, Price, O, Penman, T (2023) Health costs of wildfire smoke to rise under climate change. *Npj Climate and Atmospheric Science* **6**,

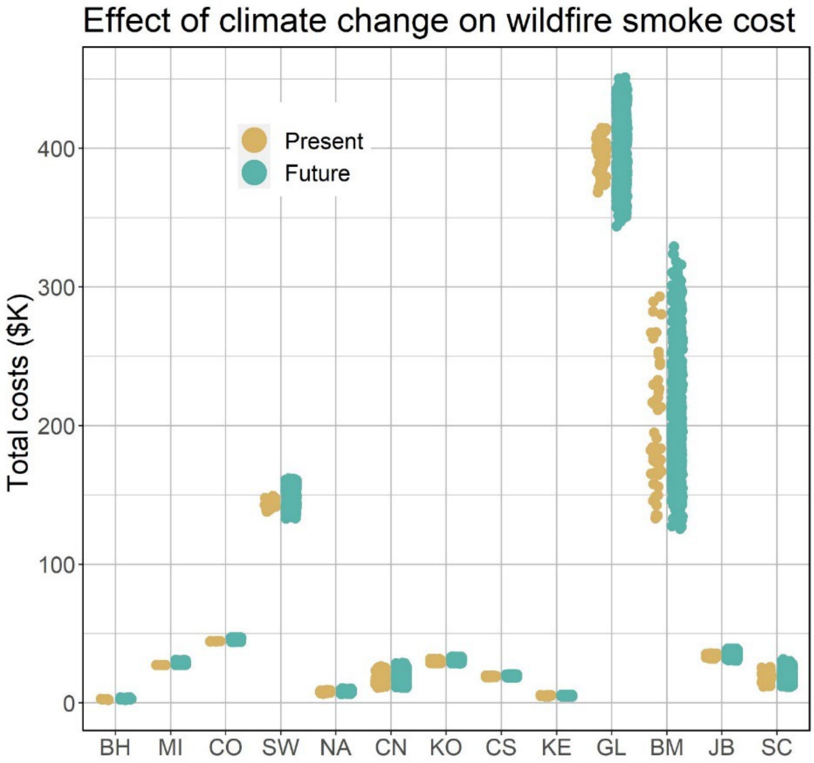


Figure 6.6 Climate change effects on wildfire smoke health costs under all treatment rates and locations for multiple landscapes. Each marker shows a different treatment strategy, but they are often overlapping because of the scale. Orange shows results present costs, green shows future costs. There is a large degree of overlap in many landscapes, but a greater cost overall particularly in Blue Mountains (BM) and Gloucester (GL). See Figure 2 for case study details.

The global health burden from wildfire smoke is expected to worsen under climate change, yet we lack quantitative estimates of the economic costs of increased mortality and hospital admissions for cardiovascular and respiratory conditions. Using a quantitative wildfire risk assessment framework and a 12-member climate model ensemble, we find a median increase in wildfire smoke health costs of 1–16% by 2070 across diverse landscapes in south-eastern Australia. Ensemble maximum cost increases (5–38%) often exceed abatements from fuel treatment, while costs decline moderately (0–7%) for the ensemble minimum. Unmitigated climate change will increase the health burden of wildfire smoke and undermine prescribed burning effectiveness.

Clarke, H, Cirulis, B, Borchers-Arriagada, N, Storey, M, Ooi, M, Haynes, K, Bradstock, R, Price, O, Penman, T (2023) A flexible framework for cost-effective fire management. *Global Environmental Change-Human and Policy Dimensions* **82**,

Fire management aims to change fire regimes. However, the challenge is to provide the optimal balance between the mitigation of risks to life and property, while ensuring a healthy environment and the protection of other key values in any given landscape. Incorporating cost-effectiveness and climate change impacts magnifies this task. We present an objective framework for quantitative comparison of the risk mitigation potential of alternative fuel treatment scenarios in south-eastern Australia. There is no single optimal strategy for all values in a given region, nor for any individual value in all regions. Trade-offs are required and cost-effectiveness is highly sensitive to the addition of management values. Climate change is likely to decrease prescribed burning effectiveness and increase total costs, therefore a rethink of best practice is required. Our study highlights the need for flexibility in the development and implementation of fire management strategies, which is something that risk-based approaches can provide. We discuss prospects of extending our framework to values for which we currently lack robust quantitative information and issues of compatibility with Aboriginal cultural burning and by implication other approaches that do not stem from within the prevailing fire management paradigm.

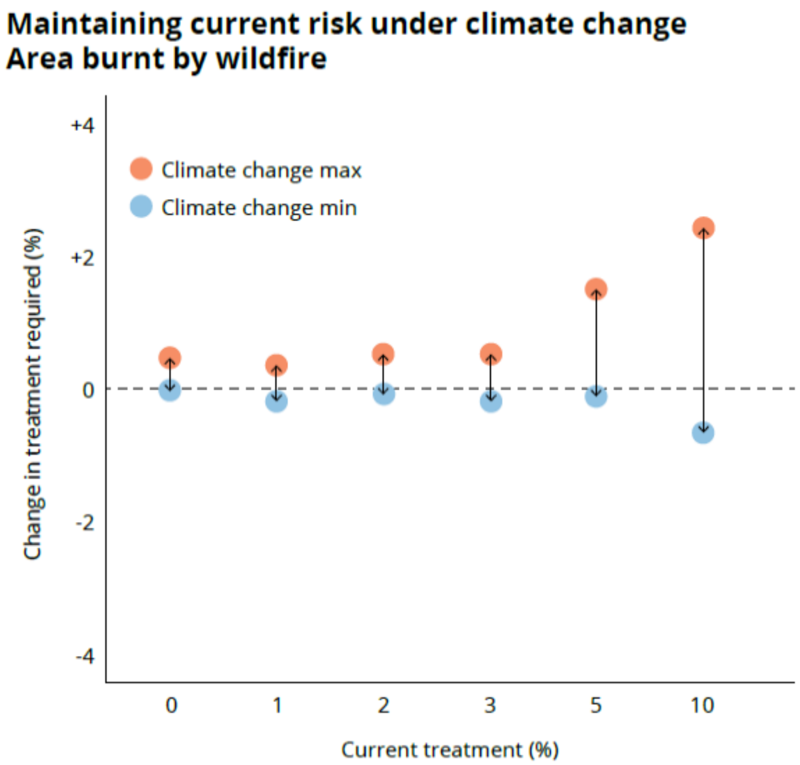


Figure 6.7 Change in treatment required to maintain current effectiveness levels under future climate change. A range of climate scenarios (height of line) are shown

Clarke, H, Cirulis, B, Penman, T, Price, O, Boer, MM, Bradstock, R (2022) The 2019-2020 Australian forest fires are a harbinger of decreased prescribed burning effectiveness under rising extreme conditions. *Scientific Reports* **12**,

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.

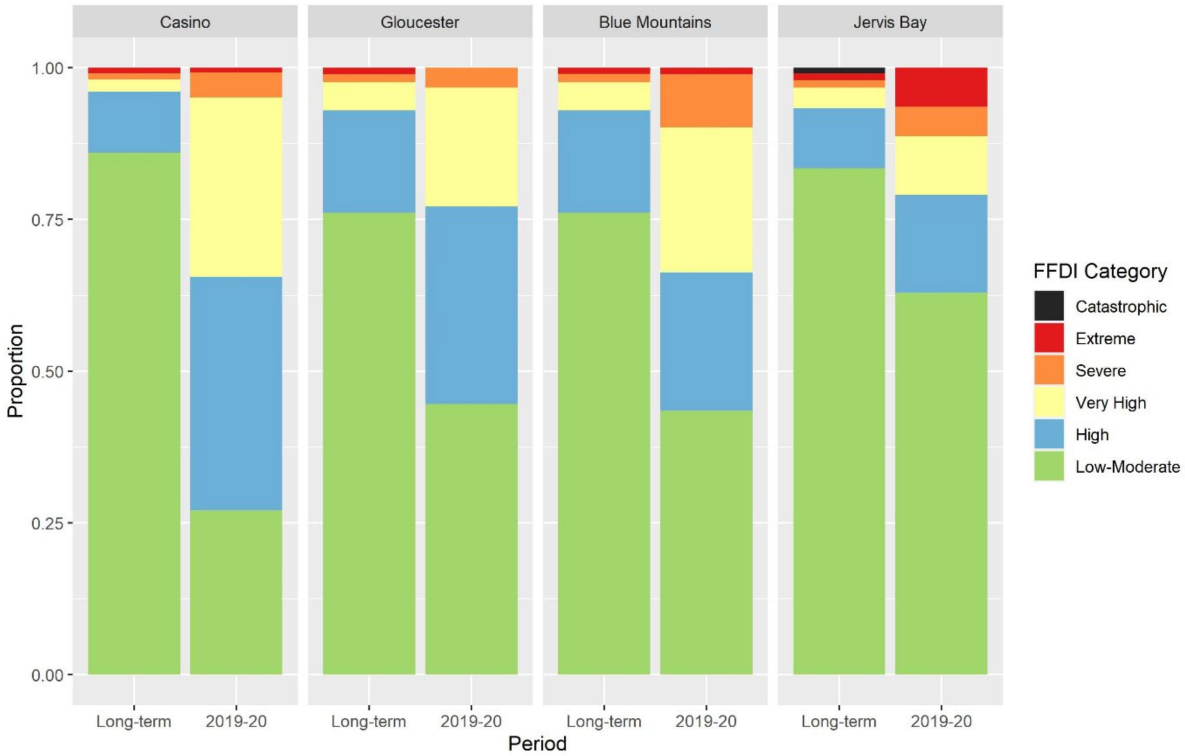


Figure 6.8 Increased fire danger conditions were seen at fire-affected areas during the 2019-20 season compared to the historical record. This decreased prescribed burning effectiveness.

Clarke, H, Evans, JP (2019) Exploring the future change space for fire weather in southeast Australia. *Theoretical and Applied Climatology* **136**, 513-527.

High-resolution projections of climate change impacts on fire weather conditions in southeast Australia out to 2080 are presented. Fire weather is represented by the McArthur Forest Fire Danger Index (FFDI), calculated from an objectively designed regional climate model ensemble. Changes in annual cumulative FFDI vary widely, from − 337 (− 21%) to + 657 (+ 24%) in coastal areas and − 237 (− 12%) to + 1143 (+ 26%) in inland areas. A similar spread is projected in extreme FFDI values. In coastal regions, the number of prescribed burning days is projected to change from − 11 to + 10 in autumn and − 10 to + 3 in spring. Across the ensemble, the most significant increases in fire weather and decreases in prescribed burn windows are projected to take place in spring. Partial bias correction of FFDI leads to similar projections but with a greater spread, particularly in extreme values. The partially bias-corrected FFDI performs similarly to uncorrected FFDI compared to the observed annual cumulative FFDI (ensemble root mean square error spans 540 to 1583 for uncorrected output and 695 to 1398 for corrected) but is generally worse for FFDI values above 50. This emphasizes the need to consider inter-variable relationships when bias-correcting for complex phenomena such as fire weather. There is considerable uncertainty in the future trajectory of fire weather in southeast Australia, including the potential for less prescribed burning days and substantially greater fire danger in spring. Selecting climate models on the basis of multiple criteria can lead to more informative projections and allow an explicit exploration of uncertainty.

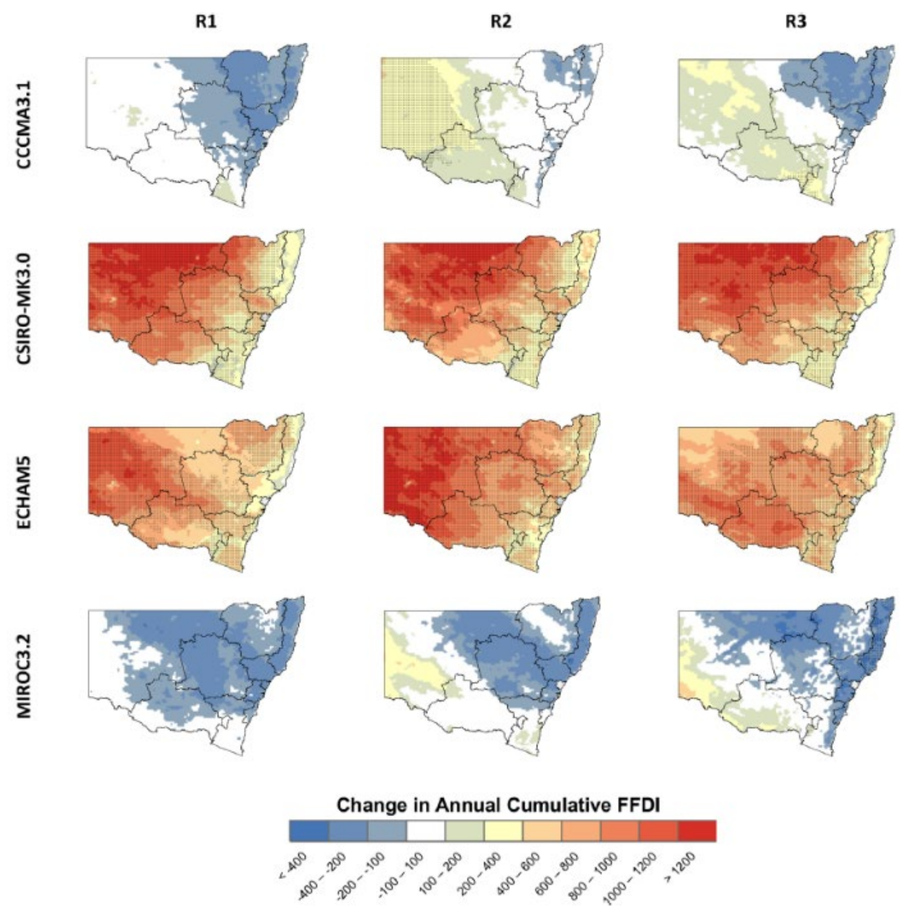


Figure 6.9 Under 12 different climate projections, FFDI is projected change by variable amounts across the state. Worst case scenarios are much more extreme than best case.

Clarke, H, Nolan, RH, De Dios, VR, Bradstock, R, Griebel, A, Khanal, S, Boer, MM (2022) Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand. *Nature Communications* **13**,

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.

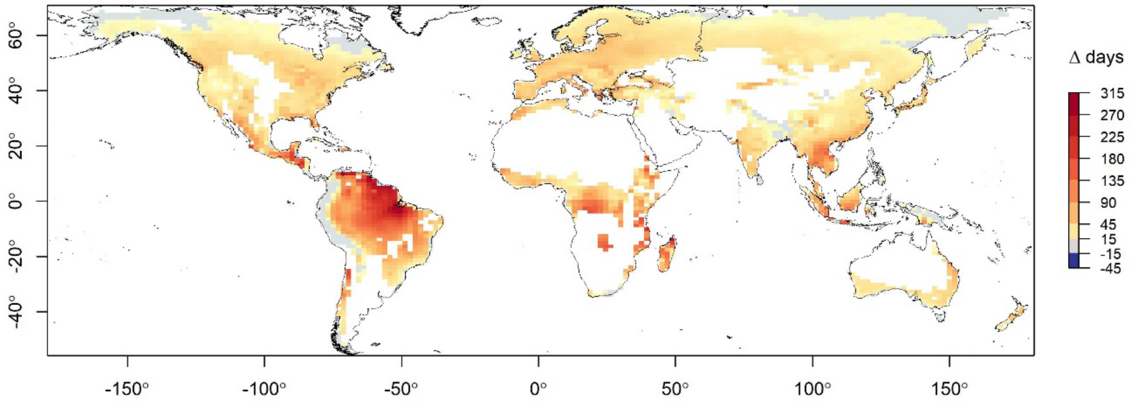


Figure 6.10 An increase in the number of days of high flammability are projected for the world's forests, based on the link between current vapour pressure deficit and current fire activity.

Full publications list

Borchers-Arriagada, N, Bowman, D, Price, O, Palmer, AJ, Samson, S, Clarke, H, Sepulveda, G, Johnston, FH (2021) Smoke health costs and the calculus for wildfires fuel management: a modelling study. *Lancet Planetary Health* **5**, E608-E619.

Borchers-Arriagada, N, Palmer, AJ, Bowman, D, Williamson, GJ, Johnston, FH (2020) Health Impacts of Ambient Biomass Smoke in Tasmania, Australia. *International Journal of Environmental Research and Public Health* **17**,

Bradstock, R, Bedward, M, Price, O, Clarke, H, Cirulis, B, Penman, T (2023) Bushfire risk mitigation under contemporary management: a case study of potential fuel treatment effectiveness across NSW, se Australia. Centre for Environmental Risk Management of Bushfire, University of Wollongong, Wollongong.

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**, 414-426.

Clarke, H, Cirulis, B, Borchers-Arriagada, N, Bradstock, R, Price, O, Penman, T (2023) Health costs of wildfire smoke to rise under climate change. *Npj Climate and Atmospheric Science* **6**,

Clarke, H, Cirulis, B, Borchers-Arriagada, N, Storey, M, Ooi, M, Haynes, K, Bradstock, R, Price, O, Penman, T (2023) A flexible framework for cost-effective fire management. *Global Environmental Change-Human and Policy Dimensions* **82**,

Clarke, H, Cirulis, B, Penman, T, Price, O, Boer, MM, Bradstock, R (2022) The 2019-2020 Australian forest fires are a harbinger of decreased prescribed burning effectiveness under rising extreme conditions. *Scientific Reports* **12**,

Clarke, H, Evans, JP (2019) Exploring the future change space for fire weather in southeast Australia. *Theoretical and Applied Climatology* **136**, 513-527.

Clarke, H, Gibson, R, Cirulis, B, Bradstock, RA, Penman, TD (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.

Clarke, H, Nolan, RH, De Dios, VR, Bradstock, R, Griebel, A, Khanal, S, Boer, MM (2022) Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand. *Nature Communications* **13**,

Clarke, H, Penman, T, Boer, M, Cary, GJ, Fontaine, JB, Price, O, Bradstock, R (2020) The Proximal Drivers of Large Fires: A Pyrogeographic Study. *Frontiers in Earth Science* **8**,

Clarke, H, Trau, B, Boer, MM, Price, O, Kenny, B, Bradstock, R (2019) Climate change effects on the frequency, seasonality and interannual variability of suitable prescribed burning weather conditions in south-eastern Australia. *Agricultural and Forest Meteorology* **271**, 148-157.

Di Virgilio, G, Evans, JP, Clarke, H, Sharples, J, Hirsch, AL, Hart, MA (2020) Climate Change Significantly Alters Future Wildfire Mitigation Opportunities in Southeastern Australia. *Geophysical Research Letters* **47**,

Fisher, R, Lewis, B, Price, O, Pickford, A (2022) Barriers to fire spread in northern Australian tropical savannas, deriving fire edge metrics from long term high-frequency fire histories. *Journal of Environmental Management* **301**,

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**,

Jenkins, ME, Bedward, M, Price, O, Bradstock, RA (2020) Modelling Bushfire Fuel Hazard Using Biophysical Parameters. *Forests* **11**, McColl-Gausden, SC, Bennett, LT, Ababei, DA, Clarke, HG, Penman, TD (2022) Future fire regimes increase risks to obligate-seeder forests. *Diversity and Distributions* **28**, 542-558.

McColl-Gausden, SC, Bennett, LT, Clarke, HG, Ababei, DA, Penman, TD (2022) The fuel-climate-fire conundrum: How will fire regimes change in temperate eucalypt forests under climate change? *Global Change Biology* **28**, 5211-5226.

Penman, SH, Price, OF, Penman, TD, Bradstock, RA (2019) The role of defensible space on the likelihood of house impact from wildfires in forested landscapes of south eastern Australia. *International Journal of Wildland Fire* **28**, 4-14.

Penman, TD, Clarke, H, Cirulis, B, Boer, MM, Price, OF, Bradstock, RA (2020) Cost-Effective Prescribed Burning Solutions Vary Between Landscapes in Eastern Australia. *Frontiers in Forests and Global Change* **3**,

Philip, S, Johnson, MS, Potter, C, Genovesse, V, Baker, DF, Haynes, KD, Henze, DK, Liu, JJ, Poulter, B (2019) Prior biosphere model impact on global terrestrial CO2 fluxes estimated from OCO-2 retrievals. *Atmospheric Chemistry and Physics* **19**, 13267-13287.