FINAL PROJECT REPORT
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OPTIMISATION OF FUEL REDUCTION BURNING REGIMES FOR FUEL REDUCTION, CARBON, WATER AND VEGETATION OUTCOMES

Final project report

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Cover: Prescribed burning in dry sclerophyll forest in Wombat State Forest, Victoria. Source: Danica Parnell.

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ACKNOWLEDGMENTS

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We would like to thank our end-users, particularly Dr Felipe Aires from National Parks and Wildlife Service, Department of Planning, Industry and Environment, NSW and Dr Adam Leavesley from ACT Parks and Conservation Services, ACT for their support and faith in our capabilities. We thank all our local and international students, undergraduates, and postgraduates alike, for enriching our project.

EXECUTIVE SUMMARY

Tina Bell, *Faculty of Science, University of Sydney, NSW*

Fire managers often have multiple objectives for a given prescribed burn centred around risk reduction and conservation of biodiversity. The ability to predict the effects of prescribed burning on the capacity of forests to deliver ecosystem services such as clean air, carbon sequestration, and a reliable and high-quality supply of water is becoming increasingly more important.

The body of research detailed in this Synthesis Report represents a concerted effort to understand the effect of prescribed burning on water quantity and carbon losses and gains in forested ecosystems in south-eastern Australia. We collected empirical data from over 100 sampling sites treated with a recent prescribed burn. The sampling strategy we used was consistent over time with target sampling variables included for estimation of overstorey and understorey biomass and direct sampling of surface and near surface fuel loads. Site selection was stratified to accommodate as much site variability as possible and to take full advantage of prescribed burn plans.

Data collected from the field was used in a variety of modelling assignments to capture the effect of prescribed burning on changes in water availability and transformation of carbon pools. Using a mixture of models and empirical sampling and analysis, we showed that there are few risks to long-term carbon and water cycles when prescribed burning is conducted on cycles of 10 or so years. Critical to this analysis is the frequency of bushfires – if the inter-fire interval of unplanned fires becomes short (e.g., <50 years) then ecosystem losses of carbon and reductions in water yield are likely to become semi-permanent features.

Our modelling endeavours ranged from relatively complex process-based models describing water and carbon balances through to simple response surface models. By exploring the transformation of carbon pools in surface fuels during prescribed burning, we developed robust yet simple-to-use models for predicting changes in total carbon and biomass in this fuel fraction. The novel application of FullCAM, a well-established model used for carbon accounting, was tested for its ability to incorporate often subtle changes in forest growth and carbon transformation associated with prescribed burning. We found this model to be relatively sensitive and recommend it to fire managers for applications such as estimation of carbon emissions. Based on our key findings, we advocate for continued research and evidence-based application of prescribed burning as a valuable land management approach.

Data assembled from peer-reviewed publications and researchers worldwide was mined for changing trends in publications concerning prescribed burning, global patterns of litterfall and standing litter, and water use efficiency of forests. These summative studies informed our research direction and chartered our progress.

A considerable number of student projects have been supported during the course of this project contributing to the training of the next generation of researchers and land managers.

END-USER PROJECT IMPACT STATEMENT

Felipe Aires, *National Parks and Wildlife Service, Department of Planning, Industry and Environment, NSW*

This report summarises an extensive volume of field work and research effort put into clarifying important knowledge gaps around the themes of fuel reduction, carbon, water and vegetation. The information contained in this report is part of a continuous effort to improve knowledge and the work done by land management agencies.

The two phases the of research included in this Synthesis Report show the evolution of investigation and development of end-user/collaborator involvement. The first phase focused on modelling primarily, water use by forests, including a carbon/vegetation growth component. The modelling effort was productive but was deemed too complex for easy operational use and a simpler approach was warranted. The second phase of research focused on modelling carbon pools using FullCAM, an operational tool already used widely for national carbon accounting in Australia; developing fine fuel triangles, investigating flammability of fine fuels and characterising transformation of fine fuel. All approaches were based on empirical data collected from the field or laboratory and have a predictive capacity. This modelling approach seems to be more suitable for end-user adoption as it requires less input data and can still detect environmental changes with good accuracy.

The investigation of FullCAM showed that the model is sensitive enough to incorporate prescribed fires and, with further refinement of input data and the ability to adjust specific model parameters, has potential to be a useful method for end-users to explore for determining carbon emissions during prescribed burning and for vegetation and carbon dynamics. This research is also useful for informing FullCAM improvements with the model developers within CSIRO.

The fine fuel triangle was developed with the intent of creating a simple-to-use tool for predicting mass and carbon content in fine fuel in either unburnt or burnt vegetation. The information needed to populate the model (actual measurement or estimation of proportions of components of surface fuel) can be collected from the field when routine measurements of fuel loads are done during pre- and post-fire site assessments. This can be used by land managers to estimate potential carbon losses from surface fuels burnt during prescribed burns.

The flammability work is for developing a robust method for determining fire severity and holds great promise for use in the field. Innovative use of near-infrared (NIR) technology to determine fire severity according to the colour and chemistry of residues could potentially be used to validate/improve satellite severity mapping or provide data for areas where satellite data is compromised.

End-uer engagement has been consistent throughout the project and became stronger during the second phase of research. There was close collaboration between fire management staff in the Blue Mountains for data collection and with researchers from CSIRO. This research has produced a substantial output of peer-reviewed papers, technical reports, and presentation of findings at conferences. There has been significant effort towards training of the next generation of fire researchers at the postgraduate level.

INTRODUCTION

The overall aim of this project was to improve the capability of land managers to use prescribed burning to manage land such that risks of loss of water yield and of carbon sequestration capacity are recognised and, where possible, minimised. A secondary aim was to explore the impacts of prescribed fire on other components of forests to improve our understanding of the complexities involved in natural systems. For example, nutrient cycling is linked to growth and water use of trees which affect litterfall and, ultimately fuel accumulation. Similarly, carbon sequestration is determined by the dynamics of carbon held in trees, the soil and accumulated fuel and the ability of prescribed fire to release carbon from these pools into the atmosphere.

Our research builds on a body of research in forested water catchments in NSW, the ACT and Victoria, that has shown differences between eucalypt forest types in effects of fire severity on subsequent stand and forest hydrology (e.g., Langford, 1976; Kuczera, 1985; Vertessy *et al*., 2001; Macar *et al*., 2006; Lane *et al*., 2010; Mitchell *et al*., 2010; Buckley *et al*., 2012; Gharun *et al*., 2013; Turnbull *et al*., 2014). Consequently, prescribed burning may be appropriate in some parts of the landscape and individual catchments but not in others.

This project also draws on previous research efforts determining the effect of prescribed burning on carbon balances in forests in southern Victoria (e.g., Volkova *et al*., 2013; Turnbull *et al*., 2014; Volkova *et al*., 2016). To improve our knowledge of strategic prescribed burning we sought to quantify variability in forests and fuels in south eastern Australia and understand the processes involved in carbon cycling to make sound predictions and continually improve the efficacy of management practices.

Land managers prioritise prescribed burning in several ways. The primary goal is for removal or reduction of fuel to minimise the risk of bushfire affecting life and property. The contribution of antecedent weather conditions to fuel moisture and current weather patterns to fire behaviour are mainly used to govern the timing of prescribed burning. Fire management in Australian forests is also guided by good knowledge of fire-response traits of key plant species (Keith, 2012). Similarly, landscape features are well understood in relation to fire – some landscape positions and aspects are more manageable than others and prescribed burning can be selected on this basis. What has been lacking, but which has become increasingly important, is increased knowledge of and a capacity for projecting the effects of prescribed burning on water (yield and quality) and carbon (e.g., capacity for fuel accumulation and carbon sequestration) of forests at a manageable spatial scale.

This Synthesis Report is presented in a format the follows the progression of our research during the tenure of the project (Figure 1). We began with collation of current information and knowledge in relation to the elements of forest water and carbon (Figure 1, *uppermost box*). This task aided the development of a logical framework that focussed our research agenda for optimising the competing outcomes of prescribed burning. From here we established an extensive set of field sites to gather empirical data from typical dry sclerophyll forests in south eastern Australia (Figure 1, *Field data collection*). We used this information to test current hydrological and carbon accounting models for their ease of use and efficacy for incorporating systemic changes due to prescribed burning (Figure 1, *Key research findings*). To address the complexities and gaps we found in current modelling capacities for water and carbon, we developed several practical tools for potential use by fire managers (Figure 1, *Application of research*). Finally, because of the involvement of our partner researchers and students, we were able to gather supporting evidence for our efforts to optimise prescribed burning with positive consequences for water and carbon. This supporting work is presented a as series of summaries in the Appendix.

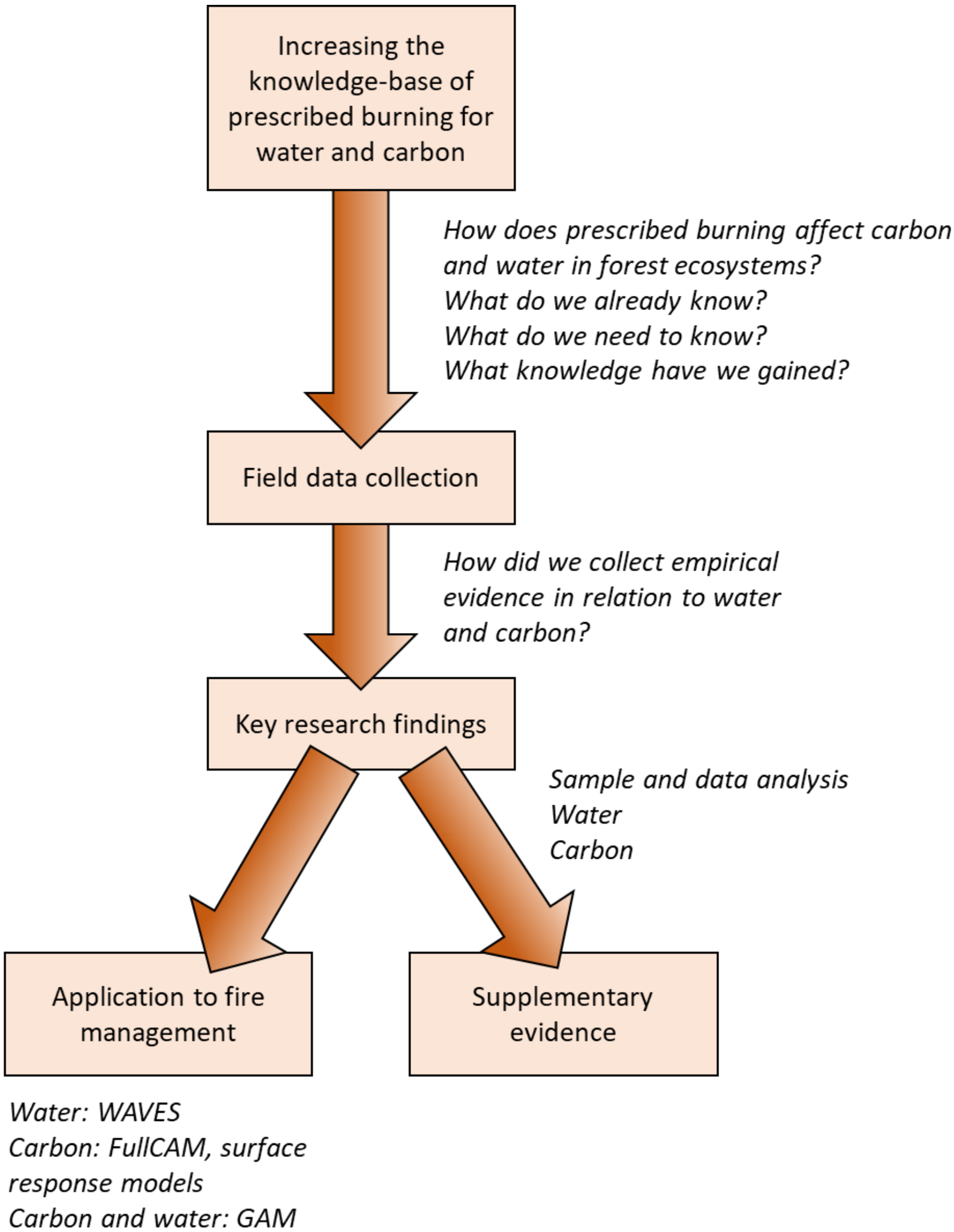

Figure 1. Conceptual diagram for research done in the 'Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water and vegetation outcomes' project presented in this Synthesis Report. WAVES: a plant growth model that incorporates Soil-Vegetation-Atmosphere Transfer models; FullCAM: full carbon accounting model; GAM: generalised additive model.

INCREASING THE KNOWLEDGE-BASE OF PRESCRIBED BURNING: WATER AND CARBON

Across the world there is strong recognition of the importance of prescribed burning for protection of life and property. Australia and parts of the United States have been at the forefront of prescribed burning programs since the early 1960s. In Australia, areas treated annually according to prescriptions for fuel reduction, ecological benefit, or a combination of both, is approximately 1.2 million ha (Adams and Attiwill, 2011), and approximately 1 million ha in the United States (Ryan *et al.,* 2013). In Australia, prescribed burning is practiced in a diversity of locations and vegetation types to reduce the incidence and extent of bushfires. In recent years, there has been a groundswell to improve our understanding of the benefits and trade-offs of intentionally putting fire into a landscape, not only to develop a more nuanced knowledge of the effectiveness of such practices, but also the ecological effects of repeated fires and their social and economic impacts.

WHAT DO WE ALREADY KNOW ABOUT PRESCRIBED BURNING?

Literature reviews are traditionally done to provide insights for future directions of research, but they can also be used to reflect on the advancement and impacts of research. For both purposes, we collected peer-reviewed publications describing research related specifically to prescribed burning from the last 20 years (since 2000). Key words including 'prescribed burn', 'prescribed fire', 'fuel reduction burn' and 'hazard reduction burn' were used for searching Web of Science, a popular database containing much of the peer-reviewed science literature. We systemically categorised publications according to:

i. Location of the study (i.e., Australia or international)

ii. General application (i.e., ecological or management)

iii. Fire regime (i.e., study of the effect of a single fire or multiple fires)

iv. Broad focus of the study (i.e., carbon, soil, water, biodiversity).

Some studies overlapped in their categories and were counted in more than one category, other studies were not easily placed into a specific category and, therefore, were not counted in any classification. A range of patterns emerged after examining more than 200 papers.

Location: Research in northern America (including Canada and the United States) and Australia has been the most prolific (Figure 2). Countries such as Finland, Sweden, and India, which do not traditionally use prescribed burning as a method of fuel reduction, have also recently joined this area of enquiry.

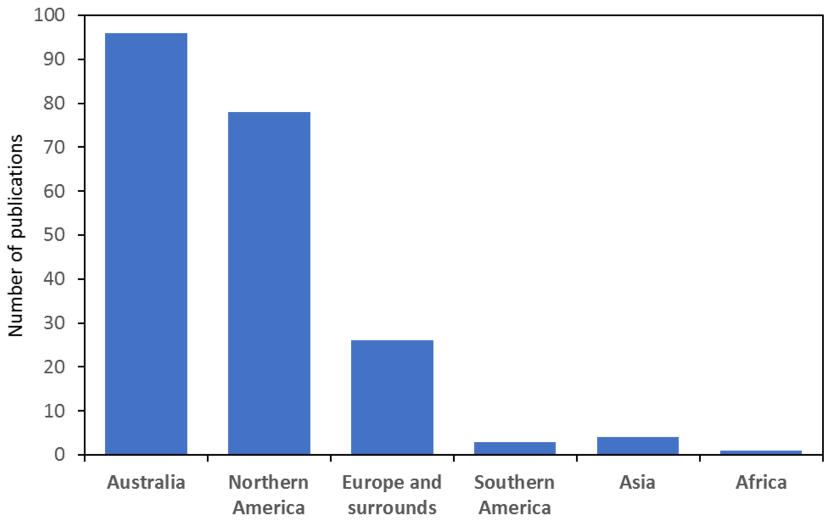

Figure 2. Ranking of locations of peer-reviewed literature investigating prescribed burning in the last 20 years. Northern America includes Canada and the United States; Southern America includes Brazil and Mexico; Asia includes China and India; Europe and surrounds includes Finland, Israel, Italy, Portugal, Spain, Sweden, Turkey, and the United Kingdom.

Over the last two decades, the publishing landscape in Australia has changed from few publications dealing with prescribed burning in the early 2000s to far more being available, particularly after the Black Saturday fires in Victoria in 2009. Unsurprisingly, the focus of these later publications was about the use of prescribed fire for bushfire mitigation. At this point, although there has been an increase in the number of publications about prescribed burning, there is no clear consensus of whether this management action was effective in reducing the likelihood of bushfire. Between 2015 and 2020, there were more publications presenting empirical and modelling research describing prescribed burning as being a practice beneficial for fire management purposes or for environmental outcomes. However, this underlying pattern is not evident when all publications from the 20-year period were considered (60% of publications being in the 'For' category; Figure 3a), which indicates the importance of understanding evolving patterns of research and the way it can be influenced.

From 2000-2020, the number of publications that investigated prescribed burning was greatest for 'environmental' studies (64%; Figure 3b), featuring some measured or modelled aspect of the biotic setting of fire, compared to 'management' studies (36%), investigating operational values (e.g., mapping, fuel loads, or fire behaviour). Of the environmental studies, plant science (25%), animal ecology (22%) or soil studies (17%) predominated (Figure 3c). In comparison, studies that focused on the effect of prescribed burning and water (2%) or carbon (8%), are few in number. Regardless of the focus of these environmental studies, in the last five years alone, there has been a remarkable increase in the number of research papers that have described predictive modelling efforts (20%), using bespoke empirical data collected directly from the field, remote observations (e.g., satellite imagery) or taken from historical datasets.

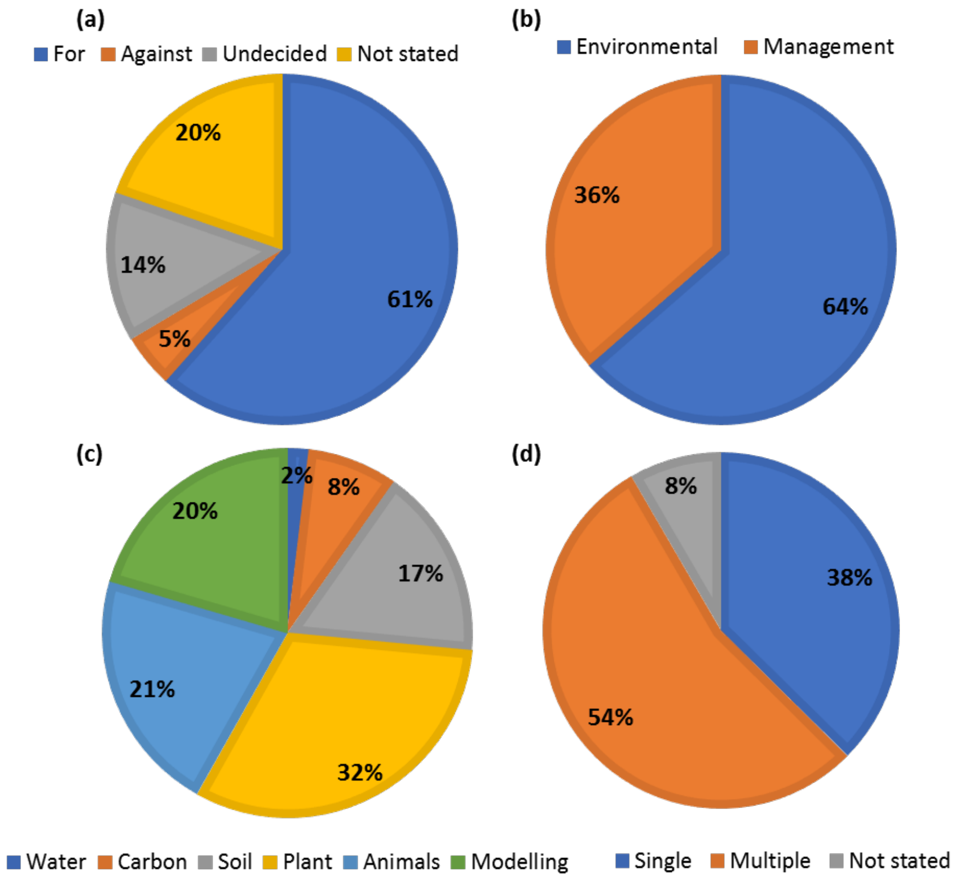

Figure 3. Patterns of broad themes in the peer-reviewed literature describing prescribed burning research in Australia since 2000: (a) efficacy of prescribed burning (for, against, undecided, not stated), (b) broad type of study (environmental or management), (c) focus of the study (water, carbon, soil, plants, animals or modelling), (d) fire regime investigated (single fire. multiple fires or not stated).

Many environmental studies undertaken in Australia over the past 20 years have investigated multiple prescribed burns at a variety of spatial and temporal scales (Figure 3d). Encouragingly, this indicates that the research informing land management is moving towards capturing landscape-scale patterns and effects of prescribed burning regimes on ecosystems. Effective land management decisions, to achieve best practice, need to be based on robust research that encapsulates environmental variability in all of its forms. Although not explicitly demonstrated from our review of the literature, this variability also needs to include diversity in vegetation types.

It is very evident that gaps still exist in research related to prescribed burning, although inroads are being made. Currently, research sits within the plant, animal, and modelling spheres, with relatively little information available on the effects prescribed fire on water and carbon. As described in this Synthesis Report, our research efforts over the past years have specifically added to the body of knowledge about the effects of prescribed burning on water and carbon outcomes. We will endeavour to continue to do this as our current research published to reach a wider and more diverse audience including end-users who are making land management decisions.

WHAT DO WE NEED TO KNOW ABOUT PRESCRIBED BURNING?

Land managers prioritise prescribed burning in several ways, with the primary aim being for the removal of fuel to minimise the risk of bushfire affecting life and property. Although there may be multiple objectives for a given prescribed burn, there is increasing incentive to understand the effects of prescribed burning on the quality and yield of water from forested catchments and carbon pools in accumulating fuel in highly flammable form as leaf litter, vegetation and bark, and less flammable forms as coarse woody debris and as decomposed matter stored in soil.

For prescribed burning programs, at an operational level, the design of proposed burns considers:

1. Reducing fuel continuity
2. Recommendations for priority based on ecological information available in the area
3. Logistical and economic considerations
4. Appropriate frequency
5. Time since last fire
6. Primary purpose of the land being managed (e.g., risk mitigation, conservation, water catchment, timber production)

These objectives have typical components of seasonality, intensity, severity, and extent that need to be included (Gharun *et al*., 2017a). Other elements such as topography, temperature, humidity, and vegetation (fuel type) across the landscape, create spatial variability and as such, add to the considerable number of factors that challenge the effective planning of prescribed burning in Australia. Early in the project, we proposed a framework that incorporates these varying requirements to maintain the efficacy of prescribed burning for protection of life and property, while considering ecological impacts (see Gharun *et al*., 2017). This framework initially had two main modules, one based on scientific knowledge and technical experience, and the other based on knowledge gaps both on operational and ecological issues. We used this framework to guide our research (Figure 4).

See Research Phase 1, Key Milestone 2.1.4 for additional details.

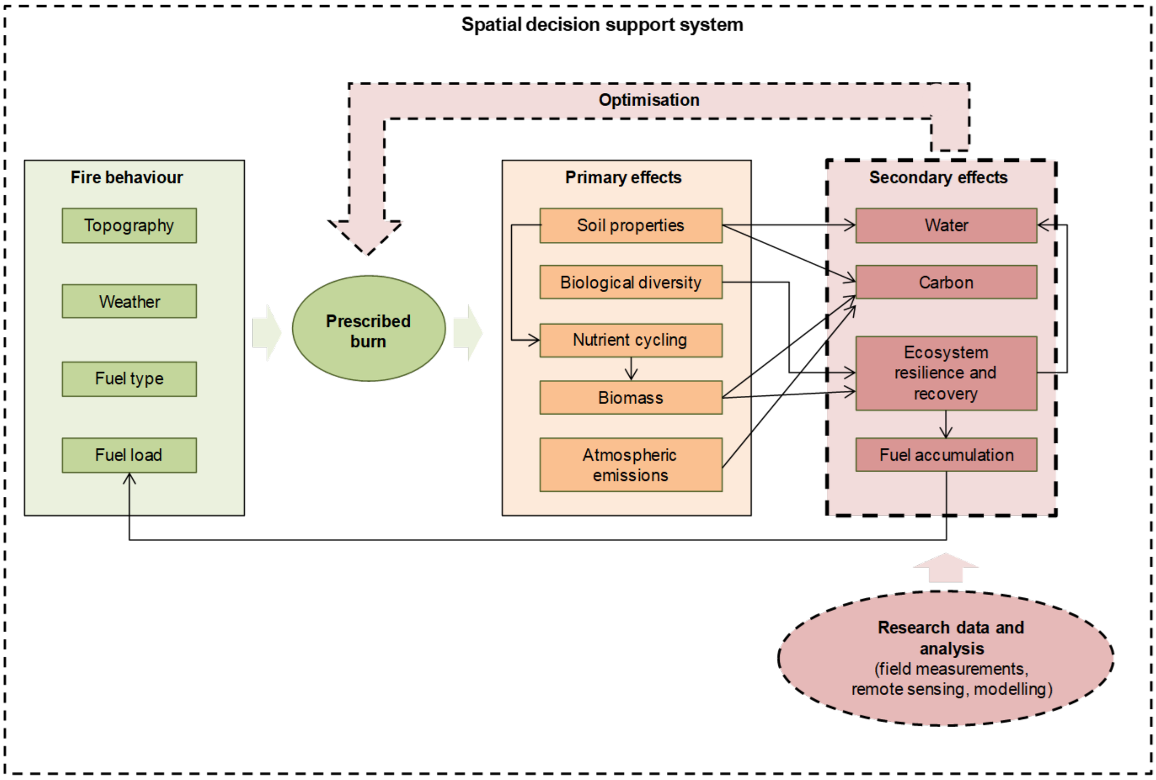

Figure 4. Conceptual framework for optimising prescribed burning for carbon, water and vegetation outcomes. From Gharun *et al*. (2017a).

WHAT KNOWLEDGE HAVE WE GAINED ABOUT PRESCRIBED BURNING?

Working with an international group of leaders in fire research, the team from the University of Swinburne developed a conceptual model of future policy and practise needs for life and asset protection (Moreira *et al*., 2020). They also contributed to a synthesis of current understanding of the role of forests in decarbonising global economies (Waring *et al*., 2020). Fire will play a significant role in any global effort to use forests – native and planted – as carbon sinks.

Much of the intended output of the project contributed by the research team led by Prof. Mark Adams out of Swinburne University is only now reaching fruition. More than 10 papers are scheduled for publication, with four now published (Adams *et al*., 2020a; b; Moreira *et al*., 2020; Waring *et al*., 2020) and five more being either submitted or close to submission (Adams *et al*., 2020a; b; Neumann and Adams, 2020; Neumann *et al*., 2020; see *Publications in preparation*).

A major piece of related work was a global analysis of water use efficiency of forests over the last century (Adams *et al*., 2020a). Increases in water use efficiency are arguably the most significant and consistent responses of all forests to rising CO_2. Increases in water use efficiency are also highly significant to fire risk as they drive both soil moisture and humidity in forests (Swann *et al*., 2016).

Planned and unplanned fire has a significant role in Australia and globally for modification of carbon pools in forested ecosystems.

FIELD DATA COLLECTION

The emphasis of our research has been to increase knowledge about the effects of prescribed burning on water and carbon balances in forested ecosystems. To achieve this, the project had the ambitious goal of sampling 100 burn units to acquire empirical data to test existing catchment hydrology and carbon balance models and build new fit-for-purpose models. We started with site and state-based targets to gauge the importance of site and forest variability and scaled up to landscape-scale predictions to test model capabilities. These efforts are described in the following section.

FIELD SITES AND SAMPLING PROTOCOL

Rationale: In the field we used a 'burn unit' – a pair of plots within a site that were measured and compared. For sites sampled in Victoria (Figure 5a), plots were sampled before ('pre-fire') and shortly after ('post-fire') (Table 1). For sites sampled in NSW and the ACT (Figure 5a and b), the pair of plots were in adjacent burnt and unburnt areas and were sampled at the same time (referred to as paired 'burnt' and 'unburnt' plots) (Table 1).

Site selection: In all cases, sites were sampled within a maximum of 4 weeks after the prescribed burn and, in most cases, within 1-2 weeks of the burn. Paired sampling plots were matched according to aspect and were located within 100-200 m of each other (e.g., either side of a containment line or cleared track). Wherever practical, plots sampled within a site were located with similar aspect and altitude. Sites selected had not been burnt for at last 10 years prior to the prescribed burn and for some location in Victoria, had not been burnt for up to 50 years. We acknowledge that we were restricted in plot selection according to the burn area, access, vegetation, and soil type. However, the unifying feature across all sites in Victoria, NSW and the ACT was sampling of 'dry sclerophyll forest' representing the typical vegetation of much of south eastern Australia (i.e., present extent of more than 234,250 km^2; Commonwealth of Australia 2017).

A total of 66 burn units were sampled during the first phase of research (July 2014-June 2017) (Table 1). This included nine sites (27 burn units) previously sampled in Victoria, 13 sites (39 burn units) sampled in NSW and the ACT (Figure 5a). Data from these sites were used to explore temporal and spatial variation in vegetation/fuel after disturbance (see Section 3).

In the second phase of research (July 2017-June 2020) another 12 burn units were sampled (Figure 5b). At this point, sampling efforts were refocused, and sites were selected in close consultation with fire agencies. The emphasis here was to answer more specific site-based questions posed by land managers about the efficacy and consequences of prescribed burning. Our remaining sampling efforts (27 plots) incorporated a range of sites in dry sclerophyll forests of low and high productivity sites to supplement our studies for development of the fine fuel model (Table 2).

Table 1. Details of burn units (paired sites sampled before/after fire or in adjacent unburnt/burnt areas) sampled throughout the project. NA = data not available.

Burn unit number	Site name	Sampling condition	Latitude	Longitude	Elevation (m asl)	Ignition date	Mean tree diameter (cm)	Mean tree height (m)
VICTORIA								
1-3	Frogs Hollow	Pre-/post-fire	-37.66	148.06	30	8 April 2011	39.2	25.0
4-6	Upper Tambo	Pre-/post-fire	-37.83	148.02	81	25 February 2011	38.0	31.9
7-9	Poddy	Pre-/post-fire	-37.68	148.90	133	10 April 2013	47.5	33.8
10-12	South Boundary	Pre-/post-fire	-37.60	148.32	254	24 February 2011	81	41.8
13-15	Sandy Point	Pre-/post-fire	-37.77	148.01	85	9 April 2013	39.0	29.4
16-18	Oliver	Pre-/post-fire	-37.73	148.78	110	3 April 2012	36.8	34.8
19-21	Gravel	Pre-/post-fire	-37.65	148.06	158	8 April 2011	38.7	32.3
22-24	Patrol	Pre-/post-fire	-37.71	148.84	110	2 April 2012	37.6	35.2
25-27	Pettmans	Pre-/post-fire	-37.68	148.95	158	8 April 2011	36.9	31.4
ACT								
28-30	Googong	Unburnt/burnt	-35.52	149.29	767	11 March 2015	24.1	11.2
31-33	Tidbinbilla	Unburnt/burnt	-35.46	148.90	869	17 March 2015	27.5	12.1
34-36	Wrights Hill	Unburnt/burnt	-35.88	148.94	1271	18 March 2015	27.6	15.5
37-39	Cotter	Unburnt/burnt	-35.60	148.80	1234	30 March 2015	37.5	13.9
NSW								
40-42	Haycock Trig	Unburnt/burnt	-33.45	151.09	230	19 August 2015	21.8	NA
43-45	Helicopter Spur	Unburnt/burnt	-33.80	150.51	450	17 August 2015	19.6	NA
46-48	Spring Gully	Unburnt/burnt	-34.09	151.15	41	14 August 2015	17.4	NA
49-51	Paterson	Unburnt/burnt	-33.53	150.58	468	19 August 2015	18.4	NA
52-54	Lakesland	Unburnt/burnt	-34.16	150.49	465	13 September 2105	23.0	NA
55-57	Martins Creek	Unburnt/burnt	-34.30	150.44	552	8 March 2016	21.8	NA
58-60	Joadja	Unburnt/burnt	-34.37	150.21	713	5 March 2016	22.7	NA
61-63	Kief Trig	Unburnt/burnt	-33.29	150.94	200	14 April 2016	27.5	NA
64-66	Left Arm	Unburnt/burnt	-33.36	150.80	259	1 April 2016	21.9	NA
67-69	Rocky Waterholes	Unburnt/burnt	-34.32	150.47	613	12-14 April 2018	26.2	13.6
70-72	Lawsons Ridge	Unburnt/burnt	-33.69	150.44	676	19 May 2018	28.5	14.3
73-75	Belmore Crossing	Unburnt/burnt	-34.51	150.57	627	10 April 2018	35.4	14.1
76-78	Oak Ridge	Unburnt/burnt	-34.27	149.93	944	30 May 2018	45.5	26.2

Table 2. Details of additional plots sampled in Phase 2 of the project for supplementary data related to surface fuel studies. NA = data not available.

Plot number	Site name	Sampling condition	Latitude	Longitude	Elevation (m asl)	Mean tree diameter (cm)
79-83	Wombat	Unburnt	-37.49	144.19	718	39.1
84-88	Orbost	Unburnt	-37.59	148.76	371	41.0
89-91	Arcadia	Unburnt	-33.40	184.53	142	NA
92-94	Halls Creek	Unburnt	-33.36	184.55	206	NA
95-97	Booker Road	Unburnt	-33.65	150.64	264	NA
98-100	Whitecross Road	Unburnt	-33.66	150.61	336	NA
101-103	Stringybark Woodland	Unburnt	-34.56	150.00	625	45.4
104-106	Grassy Box Woodland	Unburnt	-34.56	150.00	625	35.6

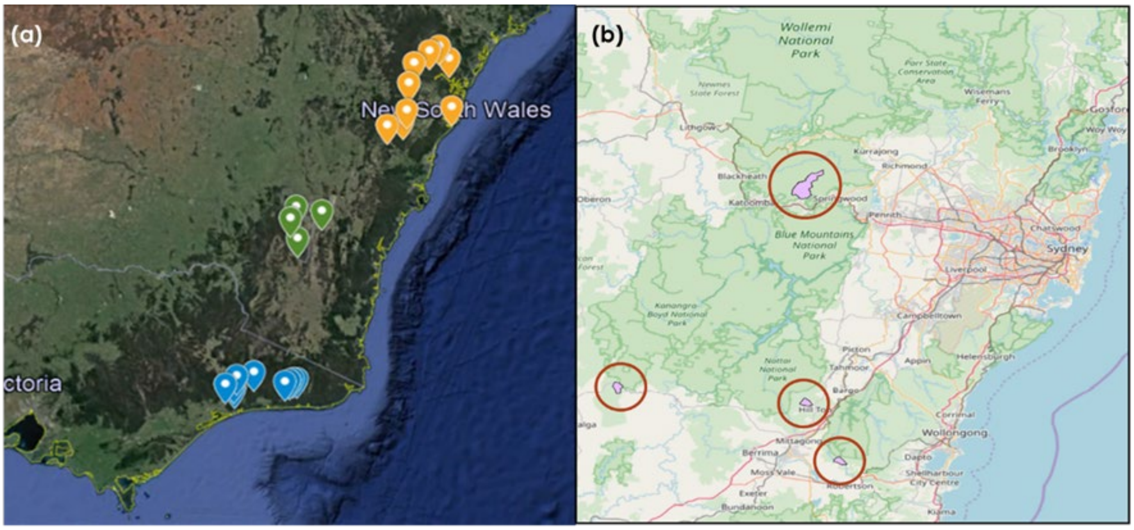

Figure 5. Sites sampled in dry sclerophyll forest in south eastern Australia: (a) 12 burn units in the ACT, 27 burn units in NSW and 27 burn units in Victoria, (b) sites sampled in the Blue Mountains in 2019 totalled 12 burn units.

Sampling variables: For each burn unit we measured a range of vegetation (fuel) and soil properties in relation to prescribed burning in a consistent and systematic way (Table 3; Gharun *et al*., 2017b). Fuel components included surface (litter and coarse woody debris), near-surface (ground cover and biomass), elevated (understorey) and canopy (overstorey) biomass, and overstorey and understorey leaf area. Soil properties included soil pH and electrical conductivity, total carbon and total nitrogen.

The empirical data collected have been used to test models to estimate the movement and transformation of carbon in forest ecosystems. The data have also been used for spatial modelling to upscale point observations for estimates of carbon pools across the landscape. These efforts will assist end-users with carbon accounting associated with their current and future land management practices.

Table 3. The nature and scale of sampling used in study sites.

Variable	Scale

Overstorey biomass	Plot
Overstorey leaf area index	Plot
Understorey biomass	Subplot
Understorey leaf area index	Plot
Ground cover biomass	Subplot
Litter biomass	Subplot
Visual fuel hazard assessment	Plot
Litter carbon and nitrogen content	Subplot
Soil pH and EC	Plot
Soil bulk density	Plot
Soil carbon and nitrogen content	Plot

Vegetation: Our field sites encompassed mixed-species dry sclerophyll forests in south eastern Australia. In Victoria, sites were classified as Lowland Forest (Ecological Vegetation Class 16; Department of Sustainability and Environment, 2004) dominated by Yellow Stringybark (*Eucalyptus muelleriana*), White Stringybark (*E. globoidea*) or Yertchuk (*E. consideniana*). In the ACT, sites were established in tall-open forests dominated by Brittle Gum (*E. mannifera*), Red Box (*E. polyanthemos*), White Gum (*E. rossi*), Apple Box (*E. bridgesiana*) Narrow-leaved Peppermint (*E. radiata*) and Broad-leaved Peppermint (*E. dives*).

In NSW, five sites sampled in the Hawkesbury region were classified as a Sydney Hinterland Dry Sclerophyll Forest, dominated by Beyer's Ironbark (*E. beyeriana*), Red Bloodwood (*Corymbia gummifera*), Narrow-leaved Stringybark (*E. sparsifolia*) and Grey Gum (*E. punctata*) (Keith, 2004). The four sites sampled in the Nattai region were a combination of Sydney Coastal Dry Sclerophyll forest and Sydney Montane Dry Sclerophyll forest. These forests were dominated mainly by Sydney Red Gum (*Angophora costata*), Blue Mountain Ash (*E. oreades*), Brown Stringybark (*E. blaxlandii*) and Broad-leaved Scribbly Gum (*E. haemastoma*) and Narrow-leaved Scribbly Gum (*E. racemosa*) (Keith, 2004). Vegetation of the four sites in the Blue Mountains was classified as a Sydney Coastal Dry Sclerophyll Forest at elevations from 750-1200 m (Keith, 2004). Vegetation at sites with high elevation were dominated by Brown Barrel (*E. fastigata*) mixed with Mountain Gum (*E. dalrympleana*), Narrow-leaved Peppermint (*E. radiata*), Messmate Stringybark (*E. obliqua*) and Blackwood (*Acacia melanoxylon*). Sites located on slopes and ridges were dominated by Brittle Gum (*E mannifera*), Broad-leaved Peppermint (*E. dives*), Red Stringybark (*E. macrorhyncha*) and White Gum (*E. rossi*).

KEY RESEARCH FINDINGS

SAMPLE AND DATA ANALYSIS

From analysis of data collected from a subset of field sites located in Victoria and the ACT, we wanted to answer the following questions:

i. How much variability is captured in measurements collected at different spatial scales?

ii. What is the optimal number of sampling plots required for statistically robust characterisation of burnt areas?

iii. How can land managers improve their assessment of the effectiveness of prescribed burning?

Our results showed that coarse woody debris is as variable at the small scale (plot, m) as it is at the landscape scale (km). For certain fuel components, such as litter biomass (in unburnt areas), overstorey biomass and leaf area, and soil properties such as total carbon and total nitrogen, samples taken at the small (plot) scale were indicative of variation at the larger scale of an individual prescribed burn and more broadly across the landscape. Variability between different spatial scales increased in burnt plots for multiple components of the vegetation including litter, coarse woody debris, small tree biomass, carbon content in the live ground cover (Figure 6; Gharun *et al*., 2017b).

Application in research: This information allowed us to modify our choice of sampling location and frequency accordingly using site stratification to reduce inherent variability.

The assumption that spatial variability in soil and vegetation variables after prescribed burning is similar to pre-fire conditions does not hold. Measurement variability does not increase with scale equally for all fuel components.

Suitable sampling frequency is required for different components of forested ecosystems.

See Research Phase 1, Key Milestone 2.4.2 for additional details.

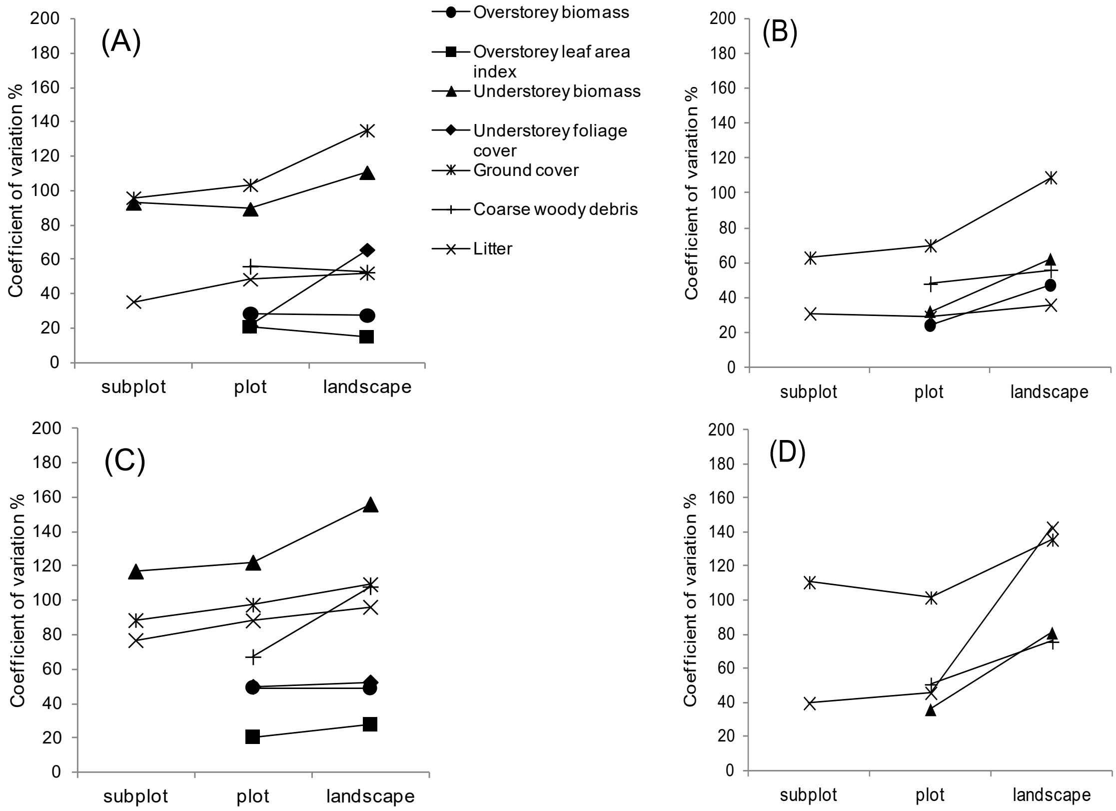

Figure 6. Mean coefficient of variation (CV, %) for fuel properties for (A) unburnt in the ACT (A) or in Victoria (B) before fuel reduction burning and burnt in the ACT (C) burnt or in Victoria (D) after fuel reduction burning. For measurements collected at the plot scale (e.g., coarse woody debris, overstorey biomass, understorey foliage cover, and leaf area index), mean variation at the plot-scale was calculated as the CV of three plots averaged over the landscape units and at the landscape-scale was calculated as the CV of one random plot from each landscape unit averaged across all landscape units (average of three groupings). Overstorey leaf area index and understorey foliage cover (%) were only measured in the burnt and unburnt plots (A and C). Figure from Gharun *et al.* (2017b).

WATER

The first phase of our research was directed towards determining the effects of planned fire on forest hydrology. We did this by using data collected from field sites in south eastern Australia (NSW, Victoria, and the ACT), both before and after prescribed burns and using a process-based model (WAVES). We found that, for a single prescribed burn, there was only a small effect on total forest evapotranspiration (ET; 10-150 mm yr^{-1}) and, for a period of time (months to >1 year depending on the site), the availability of soil moisture was greater than before the fire (Figure 7). The main impact of prescribed burning on water availability was due to changes to interception of rainfall by understorey vegetation and evaporation of water from soil surfaces as direct consequences of removal of understorey vegetation and surface litter. Furthermore, removal of these two fuel layers was likely to indirectly affect the microclimate below the forest canopy further influencing canopy ET. Growth models embedded in WAVES assume that any additional water will be used by overstorey trees with little impact on water yield. However, the magnitude of the effect of prescribed burning was very much site- and vegetation-specific (Figure 7; Gharun *et al.*, 2018).

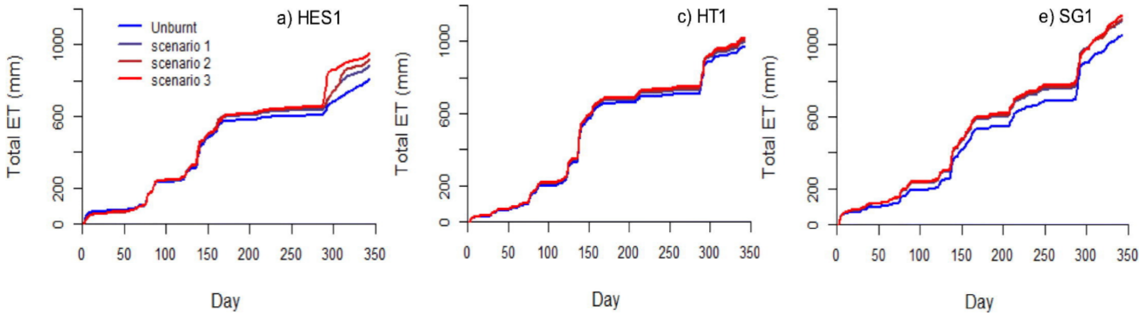

Figure 7. The effect of fuel reduction burning on total evapotranspiration (total ET) of eucalyptus forests was marginal. Each panel shows cumulative ET one year after fire in forest sites in south eastern Australia: (a) Helicopter Spur (HES1), (b) Haycock Trig (HT1) and (c) Spring Gully (SG1). Total evapotranspiration is compared among unburnt forest and when all litter is removed (scenario 1), when all litter and 50% of the understorey is removed (scenario 2), and when all litter and all of the understorey is removed (scenario 3). Graphical abstract from Gharun *et al.* (2018).

Application in fire management: One of the guiding principles that we followed in our research was that carbon and water processes are coupled in forests and need to be modelled in combination. The WAVES model achieved this but the number of input parameters (24 parameters), although modest compared to other models available (e.g., CASTANEA, a physiologically process-based model used for predicting carbon and water balances in even-aged monospecific forests, requires more than 100 input parameters; Dufrêne *et al.*, 2005), was deemed too complex for easy operational use. In addition, the sensitivity to variability in soil and vegetation inputs was untested.

In forested ecosystems, the hydrological changes associated with a single prescribed burn are generally small. These include a relatively small change in water use by trees (evapotranspiration) and a transient increase in moisture availability in the soil.

See Research Phase 1, Key Milestones 1.2.2 and 4.3.3 for additional details.

GAMS modelling: A simpler approach was warranted. For this we used a generalised additive model (GAM) using readily available information (11 parameters). These included remotely sensed data for estimating ET (enhanced vegetation index), climate variables (short- and long-term rainfall, maximum and minimum daily temperature, solar radiation), geographical data (location, elevation, aspect, slope) and soil properties (total carbon:nitrogen ratio). We found that vegetation and climatic variables were the best predictors for changes in ET whereas none of the soil or terrain variables were identified as being important factors. Using this approach, we found that change in ET due to prescribed burning was found to be vegetation specific.

There were limitations to this later study as no hydrological data were available for our sites which would have allowed changes to ET to be interpreted according to processes associated with the water cycle. For more accurate predictions and validation of ET, additional data are required (e.g., water lost through evaporation, groundwater levels, streamflow) with associated time and cost for collection of this type of information. Empirical models which require less information and are less complex are useful for detecting environmental change whereas process-based models should be used to understand the cause of the change. This pattern has also been reinforced by our research group with short- and long-term hydrological modelling of forested catchments in south eastern Australia after wildfire (Gharun *et al.*, 2015 a, b; Raducan, 2018; Yu, 2019; Yu *et al.*, 2019).

Evapotranspiration is the strongest indicator of a change in forest hydrology given the direct effect of removal of vegetation with prescribed burning.

Change in water use by trees due to prescribed burning was found to be vegetation specific.

See Research Phase 2, Key Milestones 2.3.3 and 2.4.3 for additional details.

CARBON

As with water, we found that there is considerable variability in the effect of prescribed burning on carbon pools among fuel layers at a single point in a forest and across the landscape. For example, we found the effect of prescribed burning was minimal for overstorey trees but that the overall pool represented by trees regardless of prescribed burning was highly variable (25-350 t C ha^{-1}). Soil carbon varied considerably both before and after prescribed burning (125-270 t C ha^{-1}). We now know that the amount of carbon that is 'redistributed' during a typical prescribed burn can be as little as 20 t C ha^{-1} and as much as 140 t C ha^{-1}, some, or all of which can be converted to particulate matter and gases in smoke or remain on the forest floor. On average, 3-5% of fuel is converted into charcoal or ash. This C comes from combustion of surface litter (3-10 t C ha^{-1}), woody debris on the forest floor (1-35 t C ha^{-1}) and understorey vegetation (1-7 t C ha^{-1}).

Carbon pools in forests vary considerably in dry sclerophyll forests across south eastern Australia before, during and after prescribed burning.

However, on average, 3-5% of fuel is converted into charcoal or ash and from 5-40% is released to the atmosphere as particulate matter and gases.

Carbon response surfaces: It is possible to make estimates of changes in carbon pools using models we have developed and tested during this project. The first was a simple set of models that we developed to estimate carbon stocks in surface fuel layers in unburnt and prescribed burnt forests. These models were developed and refined using samples collected during field sampling campaigns.

Samples of the near-surface fuel layer collected within a defined sampling area were separated into fine fuel, leaves and twigs and the dry weight and carbon content of each fraction was measured. To model biomass and carbon content of surface fuels, a mixture design was used. A response surface was fitted to the mixture design using a Generalised Blending Mixture model (GBM) and a polynomial equation for each response was generated by running the GBM with varying numbers of terms included in the response surface equation. To determine the best fitting equation, Akaike information criterion (AICc) was used as a measure of the relative quality of the response surface for a given set of data in relation to other model iterations. Data were randomly assigned into an 80:20 split for training and testing of the response surface of the model. Models were also validated against a second set of data collected from both high and low productivity forest sites that improved data spread and, thus, model testing.

Application in fire management: These models can be used by land managers to determine inputs for carbon accounting including estimates of carbon emissions from prescribed burning. To estimate the respective carbon or biomass content of this sample, it is as simple as positioning the proportion percentage of each fraction in the mixture at an intersection point along a contour line in the model, much like the classic soil texture triangle (Figure 8). For example, if a surface fuel sample from an unburnt site had approximately 40% leaves, 20% fine fuel and 40% other, the biomass model predicts that it is likely to represent a fuel load of 12.6 t ha^{-1}. For a burnt site, if a surface fuel sample had approximately 25% leaves, 55% fine fuel and 20% twigs, the relevant model estimates that 6.5 t ha^{-1} remains after prescribed burning. The difference between estimates of biomass and carbon for unburnt and burnt sites is therefore equivalent to reductions in fuel load and carbon emissions, respectively.

Models used to predict changes in carbon pools in forest ecosystems vary depending on the information required by fire managers.

See Research Phase 2, Key Milestone 3.1.3 for additional details.

FullCAM: Our second modelling effort used FullCAM, an operational tool already used widely for national carbon accounting for forest management in Australia. The impact of bushfires, which cause considerable transformation of carbon pools, can be readily simulated using FullCAM. For example, using FullCAM, Norris *et al*. (2010) estimated that 2,750 million t CO_2 was emitted during wildfires from 2000-2009 in Victoria. We tested FullCAM for its versatility to incorporate smaller changes in carbon pools resulting from prescribed burning (i.e., smaller areas burnt with lower intensity fire) as this type of application had not been investigated previously.

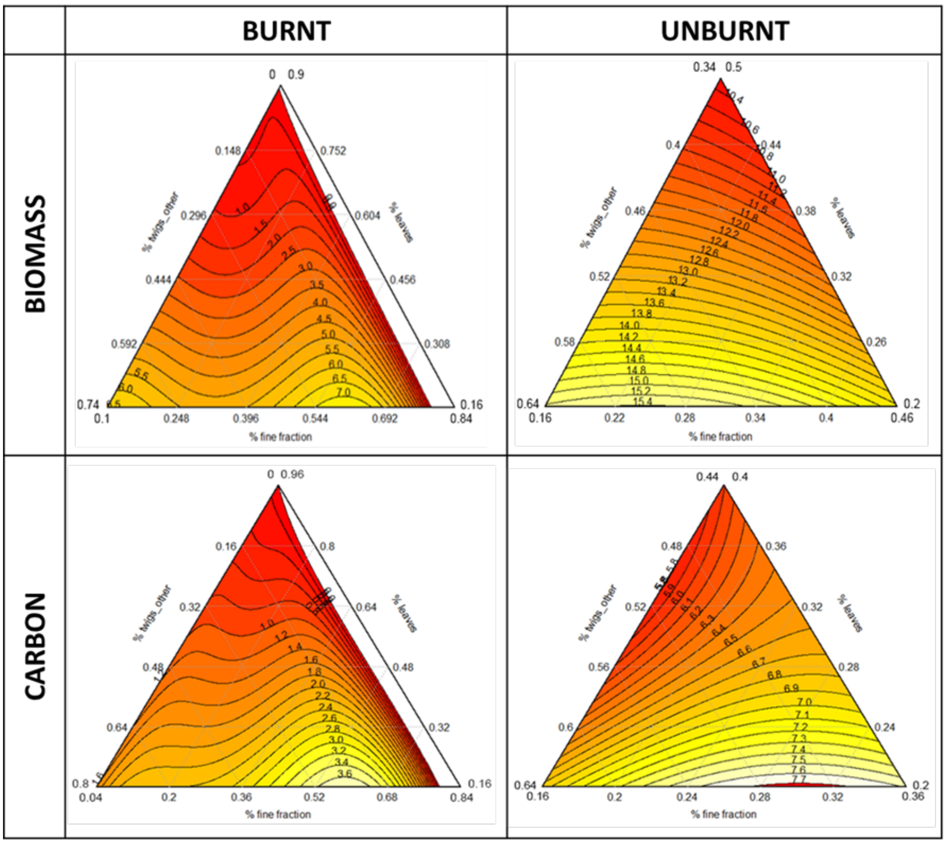

Figure 8. Carbon response surfaces developed using data from all sites sampled in the ACT, NSW and Victoria. Models presented are for estimates of biomass (t ha^{-1}) for sites that have been subject to prescribed burning (top left panel) or are unburnt (top right panel) and for estimates of carbon (t C ha^{-1}) for sites that have been subject to prescribed burning (bottom left panel) or are unburnt (bottom right panel).

FullCAM can be calibrated to accommodate a wide range of sites with various fuel types and fuel loads. It can simulate the effects of prescribed burning on the various carbon pools in an ecosystem that are directly affected. It can also simulate bushfire effects on ecosystem components, regardless of the fire history of a site. FullCAM is a useful tool to quantitatively track changes in carbon pools in ecosystems affected by fire, including emissions and carbon uptake (i.e., net ecosystem carbon exchanges with the atmosphere). We proposed that if a given area can be described in enough detail to calibrate FullCAM then this model should be able to simulate effects of prescribed fire on carbon pools. FullCAM was calibrated to each prescribed burn sampled and used to track carbon in live and dead pools and emissions into the atmosphere.

Using FullCAM to predict the effects of prescribed burning on carbon pools in forests, we found that the live vegetation would be fully regrown within 2-4 years and dead fuel levels would be partly restored (i.e., fuel accumulation). In addition, we found that additional carbon would be expected to accumulate in the fractions that are the slowest to breakdown. These include charcoal, coarse woody debris, and organic matter in soil. According to the assumptions of forest disturbance used in FullCAM, charred biomass and dead material take longer to breakdown compared to uncharred biomass. Based on this, if left undisturbed the amount of carbon in forest ecosystems would move towards a steady-state equilibrium governed by the growth capacity of the vegetation and its physical environment. Leaving forests unburned would allow them to reach and fluctuate about a steady state equilibrium (Figure 9). It is expected that the fuel load represented by the understorey would also reach a maximum level and would also fluctuate with variations in weather and other resources, canopy gaps and other disturbance factors.

In association with this research, CSIRO is currently improving the FullCAM model to better incorporate prescribed burning with modification in biomass partitioning, carbon allocation and sensitivity.

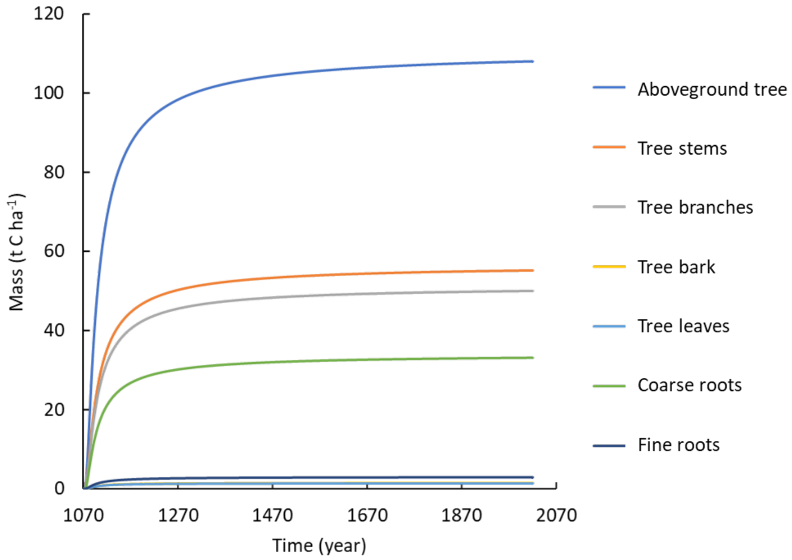

Figure 9. Undisturbed forest in steady state equilibrium using FullCAM showing the manifestation of maximum aboveground biomass. 'Aboveground tree' represents all of the tree components combined including understorey vegetation. In its current format, FullCAM has limited ability to incorporate a good representation of understorey vegetation in dry sclerophyll forests.

Application in fire management: In relation to FullCAM, questions asked of us by fire managers were:

- What is the likely effect of the prescribed burning program on carbon within each burn block of the short- to medium-term?
- What if we didn't burn? How would the carbon content change over time if the burn blocks were left in their unburned state?
- By leaving the blocks unburned, we also run the risk that they might be burned by a high intensity bushfire. What would be the likely effect of a wildfire on carbon in this scenario?

Given what we now know about FullCAM, we can answer these questions, but the answers will depend on underlying assumptions made and inputs to calibrate the model to each site.

We found FullCAM to be reasonably robust for our purposes, but modifications of input data collected from the field and the ability to partition certain pools of carbon differently would improve the capacity of the modelling. For example, FullCAM can be calibrated for a single prescribed burn to track carbon in overstorey trees and soil but simulating systematic changes in the understorey vegetation would need adjustments to parameters over time. This finding is of considerable importance as the removal of understorey vegetation (near surface fuel) is one of the main aims of prescribed burning.

Model predictions using FullCAM showed that burned live material is quickly replaced after prescribed fire with dead material (fuels) accumulating more slowly.

Recalcitrant carbon pools (charcoal, coarse woody debris, soil organic matter) are expected to increase with a prescribed burning program.

See Research Phase 2, Key Milestones 2.2.3, 3.2.2 and 3.1.3 for additional details.

Using soil carbon to estimate fire severity: In the second phase of our research, one of our focusses was to describe physical and chemical changes in surface fuels and soil during combustion. Ash and char can be used as a broad indicator of the temperature reached or heat produced during a fire and can be a key factor in understanding impacts on nutrient cycling and landscape recovery after fire (Keeley, 2009; Bento-Goncalves *et al*., 2012). There has been some recent research investigating charcoal reflectance as an indicator of the conditions under which it was produced (e.g., Vergnoux *et al*., 2009; 2011; Rosero-Vlasova *et al*., 2016; New *et al*., 2018) and we wanted to examine this potential further.

We systematically burnt fractions of surface fuel; leaves, twigs, fine fuel, and other components such as bark and soil under controlled laboratory conditions to understand the combustion process. Traditionally, fire severity is estimated on the ground using visual cues that are often subjective (e.g., ash colour, remaining litter cover) but are also measurable (e.g., trunk scorch height, minimum branch diameter). These indicators are difficult to reconcile with fire severity mapping done using remote sensing (e.g., Hammill and Bradstock, 2006), so here we ultimately aimed to develop quantitative indicators of fire intensity and severity from spectroscopy data collected using visual to near infrared (vis-NIR) scanning technology (Figure 10). We believe that there is great potential for vis-NIR spectroscopic technology to be used to determine fire severity according to the physical and chemical properties of residue after fire.

Application in fire management: Understanding the conditions under which carbon in aboveground biomass, litter and soil are transformed during combustion will provide better estimates of carbon loss as emissions. For example, it is expected that more carbon will be converted to atmospheric emissions during complete combustion (e.g., during high severity fire or fire with long residence time) compared to low severity prescribed burning. This line of enquiry would also be useful to provide information relevant for post-fire management such as potential for production of ash and post-fire as runoff.

Fire intensity and severity can be quantified to varying degrees using visual, physical, chemical and spectroscopic methods.

We can now provide underlying evidence for development of a robust and simple-to-use spectroscopic method for quantifying fire severity in the field. There is scope for linking this to satellite-based estimates of fire intensity via using this method for ground-truthing.

See Research Phase 1, Key Milestone 3.3.2 and Research Phase 2, Key Milestones 2.3.4 and 3.3.2 for additional details.

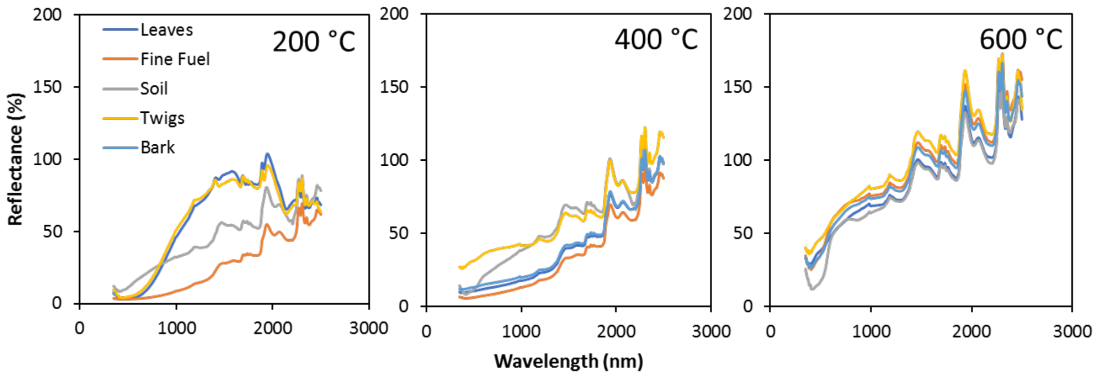

Figure 10. Reflectance values for fine fuel samples burnt at 200, 400 and 600 °C between 350 and 2500 nm. Values are indicative of an average of five replicate scans.

Litterfall and standing litter database: One of the most significant outputs from the research team at Swinburne University and collaboration authors across Australia has been the development of a national database for litterfall and standing litter in forests. The first of several papers to be derived from the data set amassed has been submitted for review at *Ecosystems* (Neumann *et al*., 2020; see *Publications in preparation*). That paper includes data compiled from peer-reviewed literature and data sets provided by researchers, including data on both fine and heavy fuels. Data was sourced for forests in Western Australia, Queensland, Northern Territory, NSW, and Victoria. The database is a result of painstaking work over a 2 to 3-year period. In addition to a comprehensive digital search via the internet, we tracked down all published and unpublished data via direct contact with authors or land management agencies or both. The result is a database with more than 3,500 records, each geographically referenced, with additional information including species, time since fire, forest age, forest structure, and many other attributes.

Aboveground litterfall (LF) is the major input to the standing litter (SL) which comprises the largest component of non-canopy fuel loads in forests. Standing litter accumulates at yearly to decadal scales and offset by litter decomposition. Our analysis shows that every year across Australia, on average about 5 t ha^{-1} of leaf and twig litter is added to SL (Figure 11a). The mean mass of SL for these components is roughly twice that (11 t ha^{-1}). Applying Olsen's (mass-balance) approach for determining decomposition constants resulted in a mean *k* of 0.46 across the continent. Litterfall, standing litter and *k* vary substantially according to decomposing material. For example, *k* is 1.11 yr^{-1} for leaves but is lower for twigs (0.41 yr^{-1}) and even lower for coarse woody material (0.06 yr^{-1}).

Litterfall and *k* can be related to precipitation, and to a lesser extent to evapotranspiration. Standing litter depends more heavily on stand structure, estimated forest age, and time-since-fire. There are major differences in composition of standing litter between south eastern Australian states on the one hand (exhibiting a 'wet climate' such that rainfall is probable throughout the year; *sensu* Hutchinson *et al*., 2005), and Western Australia, South Australia and the Northern Territory (with strongly 'seasonal climates' with distinct periods of rainfall; *sensu* Hutchinson *et al*., 2005) on the other (Figure 11b). Accumulation of heavier fuels in eastern Australia present clear and often unrecognised increases in fire risk.

Application in fire management: The compiled database is a clear step forward from previous data compilations that are geographically limited, and in some cases marred by inclusions of 'data' that are in fact modelled or 'guesstimates'. In previous compilations, different categories of fuels have been combined, as were study sites. These faults with previous compilations result in circular reasoning and argument (the fuel load model claimed to be a result of data analysis, was, in fact used to predict key data inputs). Use of those data sets results in faulty, even dangerous, conclusions (e.g., that fine fuels reach a maximum within a few years of the most recent fire).

For forests in Australia, the mean mass of standing litter is 11 t ha^{-1} and 5 t ha^{-1} of leaf and twig litter is added to this pool annually. The overall decomposition constant (Olsen's mass-balance) for forests across Australia is 0.46 but this value varies substantially.

Litterfall and *k* are related to precipitation, and to a lesser extent to evapotranspiration. Standing litter depends more on stand structure, estimated forest age, and time-since-fire.

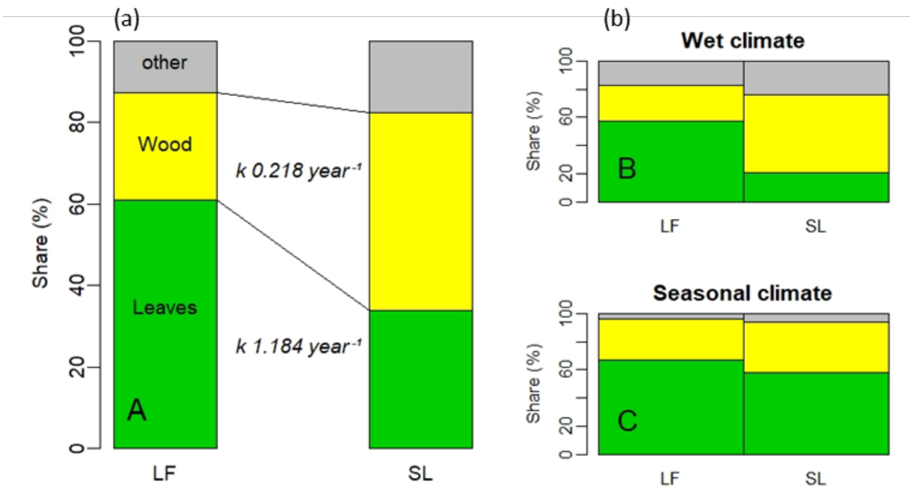

Figure 11. Proportional differences of litterfall (LF) and standing litter (SL) (a) in forests in Australia, and (B) among states with a wet climate (Victoria, NSW, ACT, Tasmania) compared to those with a more pronounced seasonal climate (Western Australia, South Australia, Northern Territory).

KEY MILESTONES

RESEARCH PHASE 1

Gharun M, Possell M, Bell TL, Adams MA (2017) Optimisation of fuel reduction burning regimes for carbon, water, and vegetation outcomes. *Journal of Environmental Management* 203, 157-170.

Bell TL, Gharun M, Possell M, Adams MA (2020) Impacts of prescribed burning on forest carbon and water. In: Prescribed Burning in Australasia: The Science, Practice and Politics of Burning the Bush, eds. Leavesley A, Wouters M, Thornton R. AFAC, 117-123.

Milestone 2.1.4: Finalised literature review of current modelling frameworks

Abstract: Fire plays a critical role in biodiversity, carbon balance, soil erosion, and nutrient and hydrological cycles. While empirical evidence shows that fuel reduction burning can reduce the incidence, severity, and extent of unplanned fires in Australia and elsewhere, the integration of environmental values into fire management operations is not well-defined and requires further research and development. In practice, the priority for fuel reduction burning is effective mitigation of risk to life and property. Environmental management objectives, including maintenance of high-quality water, reduction of CO_2 emissions and conservation of biodiversity can be constrained by this priority. We explore trade-offs between fuel reduction burning and environmental management objectives and propose a framework for optimizing fuel reduction burning for environmental outcomes.

Rationale: In this publication we reviewed the current Australia literature for prescribed burning highlighting the complexity among demands for public safety, environmental management and ecological benefits and consequences. We proposed a conceptual framework for optimising fuel reduction burning for management of C, water and fuel and where additional information and research tasks are required. We applied this framework to position our future research.

Gharun M, Possell M, Jenkins M, Poon LF, Bell TL, Adams MA (2017a) Improving forest sampling strategies for assessment of fuel reduction burning. *Forest Ecology and Management* 392, 78-89.

Milestone 2.4.2: Finalised report/manuscript of field techniques

Abstract: Land managers typically make *post hoc* assessments of the effectiveness of prescribed burning, but often lack a rigorous sampling framework. A general, but untested, assumption is that variability in soil and fuel properties increases from small (~1 m) to large spatial scales (~10-100 km). Based on a recently published field-based sampling scheme, we addressed the following questions: (i) How much variability is captured in measurements collected at different spatial scales? (ii) What is the optimal number of sampling plots required for statistically robust characterisation of burnt areas? (iii) How can land managers improve their assessment of the effectiveness of prescribed

burning? We found that measurement variability does not increase with scale for all fuel components. Results showed that coarse woody debris is as variable at the small scale (plot, m) as it is at the landscape scale (km). For certain fuel components, such as litter biomass (in unburnt areas), overstorey biomass and leaf area, and soil properties such as total carbon and total nitrogen, samples taken at the small (plot) scale were indicative of variation at the larger scale of an individual FRB and more broadly across the landscape. We then tested the hypothesis that site stratification can reduce variability between sampling plots and as a consequence will reduce the required number of sampling plots. To test this hypothesis, we used Landsat Normalized Difference Vegetation Index (NDVI) across areas treated with prescribed burning and compared the number of sampling plots required to estimate mean fuel biomass with and without stratification. Stratification of burnt areas using remotely sensed vegetation indices reduced the number of sampling plots required. We provide a model of green biomass from Landsat NDVI and make recommendations on how sampling schemes can be improved for assessment of fuel reduction burning.

Rationale: This publication bought together several milestones relating to selection of field sites, sampling protocols and analysis of empirical data. We tested if remotely sensed information could be used for stratification to select field sites to achieve greater precision and reduce costs and time associated with field sampling. We found a gain in sampling efficiency by comparing Landsat-derived NDVI with ground-based measurements. This information was used for subsequent site selection.

Gharun M, Possell M, Vervoort W, Adams M, Bell T (2018) Can a growth model be used to describe forest carbon and water balance after fuel reduction burning in temperate forests? *Science of the Total Environment* 615, 1000-1009.

Milestone 1.2.2: First reiteration of combined water and carbon model

Milestone 4.3.3: Finalised report/manuscript on development of fuel, vegetation, water and carbon models

Abstract: Empirical evidence from Australia shows that fuel reduction burning significantly reduces the incidence and extent of unplanned fires. However, the integration of environmental values into fire management operations is not yet well-defined and requires further research and development. WAVES, a plant growth model that incorporates Soil-Vegetation-Atmosphere Transfer, was used to simulate the hydrological and ecological effects of three fuel management scenarios on a forest ecosystem. WAVES was applied using inputs from a set of forest plots for one year after three potential scenarios: (1) all litter removed, (2) all litter and 50% of the understorey removed, (3) all litter and understorey removed. Modelled outputs were compared with sites modelled with no-fuel reduction treatment (Unburnt). The key change between unburnt and fuel reduced forests was a significant increase in soil moisture after fire. Predictions of the recovery of aboveground carbon as plant biomass were driven by model structure and thus variability in available light and soil moisture at a local scale. Similarly, effects of fuel reduction burning on water processes were mainly due to changes in vegetation interception capacity (i.e., regrowth) and soil evaporation. Predicted effects of fuel reduction burning on total

evapotranspiration (ET) – the major component of water balance – were marginal and not significant, even though a considerable proportion of ET had effectively been transferred from understorey to overstorey. In common with many plant growth models, outputs from WAVES are dictated by the assumption that overstorey trees continue to grow irrespective of their age or stage of maturity. Large areas of eucalypt forests and woodlands in SE Australia are well beyond their aggrading phase and are instead over-mature. The ability of these forests to rapidly respond to greater availability of water remains uncertain.

Rationale: Here we report the capacity of a well-known plant growth model to detect difference in tree water use before and after prescribed burning. WAVES, a type of Soil-Vegetation-Atmosphere Transfer (SVAT) model, was chosen as it has a good balance between complexity (i.e., does not require intricate parameterization) and usefulness (relatively easy to use and practical output information). We tested potential scenarios relevant to different consequences of prescribed burning to address the following questions:

- What is the impact of prescribed burning on plant growth (carbon gain) and hydrological processes (water quantity)?
- How long does it take for carbon and water processes to return to the pre-burning condition for each scenario?

We found the model to be effective for demonstrating patterns of forest recovery after prescribed burning, but the assumptions that need to be made make it less than ideal for management and planning purposes. The quantity of site and vegetation detail required made this model prohibitive for use by land managers.

Possell M, Gharun M, Bell T (2016) Application of statistical techniques to Pyrolysis-GC-MS data from soil to identify the impact of fire. Milestone 3.3.2 Final Report, Bushfire and Natural Hazards CRC, 22 p.

Milestone 3.3.2: Finalised report/manuscript on development of soil spectra methods/data

Abstract: Soil organic matter (SOM) has strong effects on many soil properties such as water holding capacity, soil structure and stability, nutrient availability and cation exchange capacity. Therefore, characterising soil organic matter is necessary to improve soil management. Pyrolysis coupled to gas chromatography-mass spectrometry (pyr-GC-MS) is one of many techniques that have been successfully used in this characterisation. However, a major limitation of pyr-GC-MS is that generates large amounts of mass-spectrometry data preventing fast, high throughput data analysis. This hinders our ability to identify compounds in complex matrices such as SOM that could be useful for predicting their characteristics. In this study, we aimed to investigate whether it was possible to rapidly identify significant differences among pyr-GC-MS data from soil from burnt and unburnt areas using an unsupervised statistical approach and identify the specific features that cause them. Of nearly 400 useful compounds extracted from the pyr-GC-MS data, only 15 were found to be necessary to classify between burnt and unburnt soil. We discuss how these

features could be useful in the classification of soil disturbance such as fire or, potentially, as a quantitative measure of fire impact (intensity or severity).

Rationale: Soil organic matter is a complex, heterogeneous mixture of organic materials that represents the main terrestrial carbon pool. Thus, characterisation of SOM is required to determine the mechanisms involved in its stabilisation. From a fire management perspective, this knowledge is directly related to erosion control, water quality and carbon emissions and, indirectly, for plant regrowth and fuel accumulation. This research investigated ways in which complex chemical data could be distilled into a reliable indicator of soil disturbance and, potentially, as a quantitative measure of fire impact. This work represented our first step in developing a reliable, quantitative method for post-fire assessment of fire severity and intensity on soil that can be used and interpreted by land managers.

RESEARCH PHASE 2

Parnell D, Possell M, Bell T (2020b) Estimating carbon stocks and biomass in surface fuel layers. Milestone 3.1.3 Technical Report, Bushfire and Natural Hazards CRC, 55 p.

Milestone 3.1.3: Final report/manuscript of fuel condition/vegetation model

Abstract: Here we describe a simple model that can be used to estimate carbon stocks in surface fuel layers for carbon accounting purposes. We used empirical data collected from dry sclerophyll forests in south eastern Australia to develop an easy-to-use tool to improve estimates of carbon emissions from prescribed burning. Samples of the near-surface fuel layer were separated into three fractions: fine fuel (<9 mm diameter), intact leaves, and twigs and other material such as fruits, flowers and bark and the dry weight and carbon content of each fraction was determined. To model biomass and carbon content of surface fuels, a mixture design was used. For each site, the proportion of the total fuel load of each of the three surface litter fractions was used as an independent factor (x1, x2, and x3), and the corresponding total fuel load (t ha^{-1}) or carbon content (t C ha^{-1}) was used as the dependent factor. A response surface was fitted to the mixture design using a Generalised Blending Mixture model (GBM) and a polynomial equation for each response was generated by running the GBM with varying numbers of terms included in the response surface equation. To determine the best fitting equation, Akaike information criterion (AICc) was used as a measure of the relative quality of the response surface for a given set of data in relation to other model iterations. Data were randomly assigned into an 80:20 split for training and testing of the response surface of the model. Models were also validated against a second set of data collected from high and low productivity forest sites. This additional information improved data spread and, thus, model testing.

The response surfaces fitted to data showed reasonable agreement with the data but the universal model (burnt and unburnt data from all sites combined) tended to be unreliable with both over- and underpredictions depending upon which dataset was being used for testing or validation. Universal models created using data from all burnt or unburnt sites were better than other trained models for predicting of biomass or carbon content in relation to fire history.

Rationale: This milestone is the culmination of a great deal of data analysis and testing of GBMs for a range of sites to determine the possibility of developing an 'overall' model for dry sclerophyll forests in south eastern Australia. The goal for this research was to produce an easy-to-use tool that would allow land managers to estimate biomass and carbon content in surface fuels before and after a prescribed fire. The information needed to populate the model (actual measurement or estimation of proportions of components of surface fuel) can be collected from the field when routine measurements of fuel loads are done during pre- and post-fire site assessments.

Parnell D, Bell T, Possell M (2020a) Quantifying the conversion of vegetation to ash for soil carbon fingerprinting. Milestone 2.3.4 Technical Report, Bushfire and Natural Hazards CRC, 23 p.

Milestone 2.3.4: Final report/manuscript on advances in soil carbon fingerprinting

Abstract: Samples of leaves, twigs and bark representing typical surface fuels from forests and woodlands were systematically heated and combusted under controlled conditions. Very little biomass, carbon and nitrogen was lost when heated at low temperatures to 200 °C and greatest losses occurred between 400 and 600 °C, regardless of the type of fuel burnt. Losses of carbon and nitrogen varied considerably with temperature. Carbon was lost when fuels were heated at temperatures of 300 °C or more. Nitrogen was relatively more abundant when heated at 400 °C, albeit at very low levels (less than 5%). When heating time was varied there were noticeable differences in patterns of weight loss and changes in proportions of carbon and nitrogen. This indicates that both fire intensity and residence time is likely to be important in understanding losses of carbon and nutrients during fire, particularly during low intensity prescribed burning. The use of colour of residues after heating surface fuel has the potential to determine fire severity. Existing technology such as near infra-red scanners can measure ash colour, not only indicating fire severity but also, by association, carbon and nitrogen losses from fire. Combustion studies done in a well-controlled laboratory environment could be used to interpret fireground conditions in relation to fire intensity and residence time, according to the nature and amount of charred material, charcoal and ash that remains after fire.

Rationale: Burning of vegetation as fuel causes changes in carbon pools, initially, from volatilisation of gases with heating of plant biomass followed by pyrolysis of carbon-containing compounds at higher temperatures. Estimates of gaseous emissions during fire generally assume that fuels are completely combusted regardless of whether the fire was a low intensity fuel reduction burn or a high intensity bushfire. An important step in reliable carbon accounting associated with fire is to determine the conversion rate of biomass to charred material, ash and charcoal as carbon may be moved or transformed to another pool and not completely lost to the atmosphere in gaseous form.

Parnell D, Bell T, Possell M (2020c) Near infrared spectroscopy as a new fire severity metric. Milestone 3.3.2 Technical Report, Bushfire and Natural Hazards CRC, 31 p.

Milestone 3.3.2: Final report/manuscript on soil carbon and fire severity

Abstract: Samples of leaves, twigs and bark representing typical surface fuels from forests and woodlands were systematically heated until combusted under controlled conditions in the laboratory. Change in colour of residue was described using R-conversion of the Munsell colour system and compared to colours generated from near infrared (NIR) scanning. Regardless of the method of heating used, there was very little change in physical properties or colour of residues when heated at low temperatures to 200 °C. Surface fuel samples began to thermally degrade when heated at 300 °C, which was reflected in much darker coloured residues that were mostly uniform in colour for different fuel types when determined from NIR spectroscopy. When surface fuels were combusted at temperatures between 400 and 600 °C, residues were much lighter in colour regardless of the type of fuel burnt. Again, residue colours were more uniform when described using NIR spectroscopy compared to the Munsell colour system, although differences in the consistency of residues (heterogenous production of charred material and ash) were still reflected in variations in shading. In several instances, colours resulting from NIR scans were closer to the actual colour of residues suggesting that it is a more accurate system than colour matching by eye using the Munsell colour system.

This study indicated that there is potential for NIR technology to be used to determine fire severity according to the colour of residue after fire. While the general method of colour matching is not new, the use of NIR spectroscopy can reduce inaccuracies associated with subjective colour matching and poor colour correlation when using some forms of automated colour conversion. Spectroscopic methods such as NIR can also be used to assess chemical changes in fuels during thermal decomposition. This includes quantitative losses of carbon and nitrogen and estimating fire intensity according to the temperature that were required to form a particular residue.

Rationale: Following on from spectral work completed in the first phase of our project, we wanted to further develop a way to determine fire intensity and severity of prescribed burns from residues left after combustion. The next logical step was to create residues under controlled conditions in the laboratory and develop a systematic method that describe differences among components of surface fuels and levels of heating or burning. We used both physical indicators (colour and consistency) and spectral methods (near infrared) as an advancement on qualitative methods currently described in the literature.

Based on this study, our current and future research aims to investigate the efficacy of handheld NIR systems to accurately determine fire intensity in the field for ground truthing and validating satellite imagery.

Karunaratne S, Possell M, Pepper D, Bell T (2019) Modelling emissions from prescribed burning using FullCAM. Milestone 2.2.3 Technical Report, Bushfire and Natural Hazards CRC, 46 p.

Milestone 2.2.3: Calibration of parameters associated with FRB using a full carbon accounting model

Pepper D, Bell T, Possell M, Parnell D (2020) Model predictions for fuel reduction burning of eucalypt open forest in the Greater Blue Mountains region. Milestone 3.3.1 Technical Report, Bushfire and Natural Hazards CRC, 66 p.

Milestones 3.2.2 and 3.3.1: Model predictions for FRB

Abstract: Prescribed burns are a land management tool used for reducing fuel loads in terrestrial ecosystems. Under extended drier, hotter weather conditions they might be used increasingly and more widely to help manage risk of wildfire and subsequent damage to life, property, and natural assets. They also represent a form of disturbance to ecosystems, including their biodiversity and biogeochemistry. From a biogeochemistry perspective, we apply the FullCAM carbon accounting model to eucalypt open forest sites in the greater Blue Mountains region that underwent prescribed burns and fieldwork campaigns in 2019. Field data were used to derive values and estimates that guided model calibration and helped to explore the suitability of FullCAM for simulating the effect of prescribed burning on this ecosystem type. The diameter at breast height of overstorey and understorey trees, leaf area index and surface litter fractions were key measurements for estimating production, allocation, turnover (litter input to surface debris) and breakdown (output from surface debris) of carbon pools of forest components and hence, for calibrating FullCAM. Measurements for paired burnt/unburnt plots were key to estimating loss of carbon from forest component pools to the atmosphere due to prescribed fire. Simulation of unburnt forest component pools were reasonable as a calibration, although enhancements in simulating fractions of surface litter would improve simulations of the effect of prescribed fire on forest component pools. Recommendations related to collection of field data and to model structure are made to improve alignment between model-data comparisons.

Rationale: The Full Carbon Accounting Model is a software tool that has been developed by the Australian Government, Department of the Environment and Energy as a method to report national greenhouse gas emissions from the land sector due to anthropogenic activities. This model is widely used for carbon accounting to meet national targets (United Nations Framework Convention on Climate Change, 2016; 2020). We hypothesised that FullCAM might be suitable for accounting for carbon associated with prescribed burns and for simulating the effect of prescribed burning in dry sclerophyll forests.

From the model-data comparison, it was evident that better measurements to derive estimates of understorey biomass, the twig fraction of surface litter and aboveground deadwood are needed to use the carbon accounting framework of FullCAM. While the generic framework of FullCAM is suitable for modelling carbon stocks and flows in eucalypt open forest systems, improvements to simulate the effect of prescribed burning more closely on carbon stocks and flows are required.

Yu M, Pepper D, Bell T, Possell M (2020) Detecting the effects of prescribed burning using generalised additive modelling. Milestone 2.3.3 Technical Report, Bushfire and Natural Hazards CRC, 24 p.

Milestones 2.3.3 and 2.4.3: Calibration of water and carbon model using field/existing data

Abstract: Data collected from 52 plots from sites in Victoria and New South Wales were used to test whether a simple modelling technique – a generalised additive model (GAM) – could be used in conjunction with satellite imagery to detect the effect of prescribed burning on the hydrological cycle. Evapotranspiration (ET) was selected as the strongest indicator of a change in forest hydrology given the direct effect of removal of vegetation with fuel reduction burning. Variables included in the ET GAM were site details (location, elevation, aspect, slope), soil properties (total carbon and nitrogen), climate (short-term and long-term rainfall, maximum and minimum daily temperature, solar radiation) and the enhanced vegetation index (EVI), a commonly used spectral product derived from satellite imagery. These variables were used to develop GAMs using sites in each state and combined. Results from this modelling suggested a change in ET due to prescribed burning was more obvious for sites in Victoria than in NSW. Vegetation (EVI) and climatic variables (solar radiation, df5 and df95) were the best predictors for changes in ET due to prescribed burning activities. Soil (carbon:nitrogen ratio) and terrain variables (slope, aspect, elevation) were not important factors for detecting change in ET. Limitations due to temporal and spatial differences in sampling unburnt and burnt plots and future potential for this method are discussed.

Rationale: Change detection compares differences of a point or points of reference in the landscape over time. Understanding the scope and magnitude of landscape change is important for understanding and managing interactions in the environment. Predicting changes in evapotranspiration (ET) after fire involves using both spatial and temporal variables. The correlations among these data might be linear, non-linear, independent, or co-dependent. A generalised additive model (GAM) was used in this study because of the inherent flexibility of the model to present different forms of correlations between ET and individual input variables regardless of their relationship with ET.

UTILISATION AND IMPACT

SUMMARY

Our project has several clear themes:

1. Carbon, water and nutrient interactions in wildfires and prescribed fires
2. Enhancing carbon, water, and nutrient outcomes from prescribed burning
3. Building the knowledge base for fire management in Australia

We have amassed a substantial number of outputs including peer-reviewed research published in highly ranked journals, milestone and technical reports detailing research our progress and development and contributions to national and international conferences. We have supported the development of the next generation of fire researchers by fostering postgraduate researchers and gaining the interest of future researchers by teaching students at the undergraduate level.

END-USER IMPACT

Throughout the two phases of our research our involvement with end-user agencies has progressed and strengthened. During the later stages of this project, we developed a close collaboration between operational staff in the Blue Mountains and with researchers from CSIRO. We have tested and developed models for water, and carbon with end-users in mind – Are they relatively easy to use? Are they providing useful information? Do they genuinely reflect processes in forest ecosystems? An example of our efforts is the 'fine fuel triangle'. This is a simple-to-use tool for predicting mass of fine fuel and carbon content in either unburnt or burnt vegetation. This can be used by land managers to estimate potential carbon losses from surface fuels burnt during prescribed burns. Details of application of our research to fire management are provided in '*Key research findings*'.

RESEARCH IMPACT

The major outputs from our research has been a mixture of peer-reviewed publications and technical reports (see *Publication List*). The impact of our peer-reviewed publications can be readily quantified (see Table 4). We generally publish in Q1 ranking journals (in fields of Forestry; Ecology, Evolution, Behaviour and Systematics; Management, Monitoring, Policy and Law; Chemical Engineering) and occasionally in Q2 to reach the most appropriate audience (Water Science and Technology; Mechanical Engineering). Our work has been cited consistently (Table 4). Many of the technical reports produced in Phase 2 have or will be developed into manuscripts (see *Publications in preparation*).

Table 4. Scientific impact of our peer-reviewed research. The journals *Fire* and *Frontiers in Forests and Global Change* are new and do not yet have an Impact Factor assigned (N/A). The ranking value is the SCImago Journal Rank indicator. A rank of Q1 is given to the top 25% of journals in a given subject area; a rank of Q2 is given to the 25 to 50% group. See 'Publication List' for details of these publications.

Peer reviewed article	Times cited	Journal	Ranking	Impact factor
Jenkins *et al.* (2014)	12	*International Journal of Wildland Fire*	Q1	2.640
Dijkstra & Adams (2015)	17	*Ecosystems*	Q1	4.466
Gharun *et al.* (2015a)	7	*Oecologia*	Q1	3.094
Gharun *et al.* (2015b)	6	*Agricultural and Forest Meteorology*	Q1	4.651
Gharun *et al.* (2015c)	10	*Water*	Q2	2.544
Possell *et al.* (2015)	12	*Biogeosciences*	Q1	3.920
Jenkins *et al.* (2016)	12	*Forest Ecology and Management*	Q1	3.170
Paul *et al.* (2016)	48	*Global Change Biology*	Q1	9.020
Wang *et al.* (2016)	8	*Energy and Fuels*	Q1	3.021
Dijkstra *et al.* (2017)	10	*Journal of Ecology*	Q1	5.760
Gharun *et al.* (2017a)	4	*Journal of Environmental Management*	Q1	4.175
Gharun *et al.* (2017b)	1	*Forest Ecology and Management*	Q1	3.170
Wang *et al.* (2017)	6	*Energy and Fuels*	Q1	3.021
Gharun *et al.* (2018)	4	*Science of the Total Environment*	Q1	6.551
Wang *et al.* (2019)	2	*Frontiers in Mechanical Engineering*	Q2	1.390
Yu *et al.* (2019)	0	*Water*	Q2	2.544
Gormley *et al.* (2020)	1	*Fire*	N/A	N/A
Adams *et al.* (2020a)	0	*Nature Climate Change*	Q1	25.170
Adams *et al*, (2020b)	3	*Global Change Biology*	Q1	9.020
Kruse *et al.* (2020)	1	*Frontiers in Forests and Global Change*	N/A	N/A
Moreira *et al.* (2020)	0	*Environmental Research Letters*	Q1	6.192
Neumann *et al.* (2020)	0	*Biomass and Bioenergy*	Q1	3.551
Waring *et al.* (2020)	0	*Frontiers in Forests and Global Change*	N/A	N/A

Researcher testimonials

Dr Shanti Reddy, Department of Industry, Science, Energy and Resources, National Inventory Systems and International Reporting, ACT

From your perspective, and perhaps that of the Dept of Environment and Energy/Department of Industry, Science, Energy and Resources and its objectives, do you think that having research groups like ours use and apply the FullCAM model to prescribed burning sites is beneficial in general?

Yes, although FullCAM was developed primarily for the reporting of greenhouse gas emission emissions, it can be used to support other applications as you have demonstrated in this study.

Is the interaction/collaboration beneficial?

Yes, I think so. We like to spend more time collaborating with researchers like you, however, our annual reporting cycle doesn't allow us much time for this to happen in practice, although we try our best and find time where we can.

Are aspects/results of our work beneficial?

Yes, feedback from research users like you [are] beneficial to further improve the quality and validate FullCAM outputs.

Dr Keryn Paul, Carbon Cycling and Vegetation Processes, CSIRO Land & Water, ACT

From your perspective, and perhaps that of the Dept of Environment and Energy/Department of Industry, Science, Energy and Resources and its objectives, do you think that having research groups like ours use and apply the FullCAM model to prescribed burning sites is beneficial in general?

This work is very useful for informing FullCAM improvements. In fact, hoping we can work with you on FullCAM improvements in simulating disturbance events more generally in the work program starting up next year.

STUDENT TRAINING

One of our key research impacts over the course of the project has been training of undergraduate and postgraduate students. Most notably, we have had four students graduate with postgraduate research degrees: Dr Mengran Yu, Dr Houzhi Wang, Dr Gabriela Raducan and Ms Angela Gormley. We have also had three undergraduate students complete their Honour degrees with us and we currently have five student research projects being done. We have hosted seven international students, three of which completed the research component of their postgraduate degrees while in Australia.

OUTREACH

Throughout the project we have presented at annual BNH CRC fora and workshops and national and international conferences detailing our progress made and presenting new research. A full list of conference presentations are presents at the end of the Synthesis Report (see *List of publications*).

In the first phase of our research, we developed a Hazard Note (February 2016) and provided occasional end-user updates. Since June 2018, we have produced bi-monthly newsletters for end-users and researchers to inform audiences of our progress. These have been well received and have attracted comments from end-users on occasion.

- Project and team updates, **June 2018**
- Understanding carbon pools to improve emission estimates from fires, **August 2018**
- Reconciling fuel assessment methods – comparing visual and empirical measurements, **October 2018**
- Fire effects on soil properties: case studies in south eastern Australia, **December 2018**
- Estimating carbon stocks and biomass in surface fuel layers, **February 2019**
- Effects of Sydney Coastal dry sclerophyll forest litter on fuels and fire behaviour in Hornsby Shire, **April 2019**
- Project and student updates, **June 2019**

- Approaches for investigating wildfire impacts on catchment hydrology, **August 2019**
- Ashes to ashes: the nature of ash produced from wildfires, Student Project 1, **October 2019**
- Ashes to ashes: the nature of ash produced from wildfires, Student Project 2, **December 2019**
- Flammability of dry sclerophyll forest litter, **February 2020**
- Sampling and data analysis of field sites of 40 prescribed burns – an update, **April 2020**
- Near infrared spectroscopy as a new fire severity metric, **June 2020**
- Prescribed burning for multiple objectives, **August 2020**

EXPERT OPINION

- In the aftermath of bushfires in December 2016 in Victoria, Mark Adams was interviewed for newspaper articles in The Age and radio interviews for ABC Radio 702 in Sydney and Radio National. Tina Bell was interviewed for a newspaper article in The Land and a radio interview for Deutschlandfunk/German Public Broadcasting Corporation.
- In the lead up to summer in 2018, Tina Bell did a radio interview with BBC, Sydney about the potential for an elevated bushfire risk with the predicted hot, dry summer in south eastern Australia.
- As a response to the Black Summer fires, Tina Bell had a strong media presence both within Australia (ABC news, Sydney Morning Herald, Australian Academy of Science, Australian Financial Review, Radio National, In the Know, an on-line news platform hosted by Yahoo, Open Road Magazine from the NRMA, radio stations Eastside FM in Sydney, 4ZZZ in Brisbane and UUU FM in Shoalhaven), and internationally (newspapers La Pais in Spain, Le Figaro in France, Le Temps in Switzerland, South China Morning Post in Hong Kong, BBC on-line, NU .nl. in the Netherlands, the Associated Press; JIJI Press, a Japanese news service, Danish fact checking media TjekDet, Swiss WWF Magazine; radio interviews for Quirks and Quarks, a weekly science radio show on CBC, Canada's public broadcaster, National Public Radio in the US, and Redaktion Forschung Aktuell, Germany).
- Tina Bell provided expert opinion about the impact of bushfire on soil condition (as a briefing document produced by the Australian Academy of Science) and the effect of fire retardants on ecosystems to the NSW Bushfire Enquiry.
- Recognition of Tina Bell's contribution to fire ecology in Smith *et al.* (2018).

RESEARCH COLLABORATION

- National collaboration with researchers from CSIRO towards better incorporation of prescribed burning into FullCAM.

- International collaboration with researchers from the Polytechnic of Torino and University of Padova for the European call LC-CLA-15-2020: Forest Fires risk reduction: towards an integrated fire management approach in the EU in the Horizon 2020 programme.
- International collaboration with researchers from University of California, Davis-University of Sydney as part of a collaborative fire response initiative.

NEXT STEPS

Though the formal contract with the Bushfire and Natural Hazards CRC for this project will cease at the end of September 2020, with a final administrative extension until December 2020, there are future research and reporting activities that will be presented:

- Extend our modelling capabilities by testing models using data provided for additional vegetation types from Western Australia (e.g., *Banksia* woodland and Jarrah (*Eucalyptus marginata*) forest) in collaboration with land managers and researchers from the Department of Parks and Wildlife (Western Australia).
- Continue research related to carbon transformation during fire: (a) using near infra-red spectroscopy of combustion residues to determine fire intensity, (b) detection of changes in soil carbon after fire from satellite imagery, and (c) interrogation of fire severity maps with patterns of heterogeneity of surface fuel combustion.
- Continue fuel flammability research incorporating different vegetation types and metrics for leaf form and chemistry and plant and fuel structure.
- Convert Milestone reports and student research into peer-reviewed publications (see *Publications in preparation* for details).

PUBLICATION LIST

PEER-REVIEWED JOURNAL ARTICLES

1. Adams MA, Buckley TN, Turnbull TL (2020a) Diminishing CO_2-driven gains in water-use efficiency of global forests. *Nature Climate Change* 10, 466-471.
2. Adams MA, Shadmanroodposhti M, Neumann M (2020b) Causes and consequences of eastern Australia's 2019–20 season of mega-fires: a broader perspective. *Global Change Biology* 26, 3756-3758.
3. Dijkstra F, Adams MA (2015) Fire eases imbalances of nitrogen and phosphorous in woody plants. *Ecosystems* 18, 769-779.
4. Dijkstra FA, Jenkins ME, de Remy de Courcelles V, Keitel C, Barbour MM, Kayler E, Adams MA (2017) Enhanced decomposition and nitrogen mineralization sustain rapid growth of *Eucalyptus regnans* after wildfire. *Journal of Ecology* 105, 229-236.
5. Gharun M, Possell M, Vervoort W, Adams M, Bell T (2018) Can a growth model be used to describe forest carbon and water balance after fuel reduction burning in temperate forests? *Science of the Total Environment* 615, 1000-1009.
6. Gharun M, Possell M, Jenkins M, Poon LF, Bell TL, Adams MA (2017a) Improving forest sampling strategies for assessment of fuel reduction burning. *Forest Ecology and Management* 392, 78-89.
7. Gharun M, Possell M, Bell TL, Adams MA (2017b) Optimisation of fuel reduction burning regimes for carbon, water and vegetation outcomes. *Journal of Environmental Management* 203, 157-170.
8. Gharun M, Turnbull TL, Pfautsch S, Adams MA (2015a) Stomatal structure and physiology do not explain differences in water use among montane eucalypts. *Oecologia* 177, 1171-1181.
9. Gharun M, Turnbull TL, Henry J, Adams MA (2015b) Mapping spatial and temporal variation in tree water use with an elevation model and gridded temperature data. *Agricultural and Forest Meteorology* 200, 249-257.
10. Gharun M, Amzi M, Adams MA (2015c) Short-term forecasting of water yield from forested catchments after bushfire: a case study from south-east Australia. *Water* 7, 599-614.
11. Gormley AG, Bell TL, Possell M (2020) Non-additive effects of forest litter on flammability. *Fire* 3, 12; doi: 10.3390/fire3020012
12. Jenkins ME, Bell TL, Norris J, Adams MA (2014) Pyrogenic carbon: the influence of particle size and chemical composition on soil carbon release. *International Journal of Wildland Fire*, doi: 10.1071/WF13189
13. Jenkins ME, Bell TL, Poon LF, Aponte C, Adams MA (2016) Production of pyrogenic carbon during planned fires in forests of East Gippsland, Victoria. *Forest Ecology and Management* 373, 9-16.
14. Kruse J, Turnbull T, Rennenberg H, Adams MA (2020) Plasticity of leaf respiratory and photosynthetic traits in *Eucalyptus grandis* and *E. regnans* grown under variable light and nitrogen availability. *Frontiers in Forests and Global Change* 3, 5, doi: 10.3389/ffgc.2020.00005
15. Moreira F, Ascoli D, Safford H, Adams MA, Moreno JM, Pereira JMC, Catry FX, Armesto J, Bond W, González 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, doi: 10.1088/1748-9326/ab541e.
16. Neumann M, Eastaugh C, Adams M (2020) Managing mixed *Callitris-Eucalyptus* forests for carbon and energy in central-eastern Australia. *Biomass and Bioenergy* 140, 105656.
17. Paul KI, Roxburgh SH, Chave J, England JR, Zerihun A, Specht A, Lewis T, Bennett LT, Baker TG, Adams MA, Huxtable D, Montagu KD, Falster DS, Feller M, Sochacki S, Ritson P, Bastin G, Bartle J, Wildy D, Hobbs T, Larmour J, Waterworth R, Stewart HTL, Jonson J, Forrester DI, Applegate G, Mendham D, Bradford M, O'Grady A, Green D, Sudmeyer R, Rance ST, Turner J, Barton C, Wenk EH, Grove T, Attiwill PM, Pinkard E, Butler D, Brooksbank K, Spencer B, Snowdon P, O'Brien N, Battaglia M, Cameron DM, Hamilton S, Mcauthur G, Sinclair J (2016) Testing the generality of above-ground biomass allometry across plant functional types at the continent scale. *Global Change Biology* 22, 2106-2124.
18. Possell M, Jenkins ME, Bell TL, Adams MA (2015) Emissions from prescribed fires in temperate forest in south-east Australia: implications for carbon accounting. *Biogeosciences* 12, 257-268.
19. Wang H, van Eyk PJ, Medwell PR, Birzer CH, Tian ZF, Possell M, Huang X (2017) Effects of oxygen concentration on radiation-aided and self-sustained smoldering combustion of radiata pine. *Energy and Fuels* 31, 8619-8630.
20. Wang H, van Eyk PJ, Medwell PR, Birzer CH, Tian ZF, Possell M, Huang X (2019) Air permeability of

the litter layer in broadleaf forests. *Frontiers in Mechanical Engineering* 5 doi: 10.3389/fmech.2019.00053

21. Wang H, van Eyk PJ, Medwell PR, Birzer CH, Tian ZF, Possell M (2016) Identification and quantitative analysis of smoldering and flaming combustion of radiata pine. *Energy and Fuels* 30, 7666-7677.
22. Waring B, Neumann M, Prentice IC, Adams M, Smith P, Siegert M (2020) Forests and decarbonization – roles of natural and planted forests. *Frontiers in Forests and Global Change* 3, 58, doi: 10.3389/ffgc.2020.00058
23. Yu M, Bishop T, van Ogtrop F (2018) Assessment of the decadal impact of wildfire on water quality in forested catchments. *Water* 11, 533. odi: 10.3390/w11030533

BOOK CHAPTERS

24. Bell TL, Gharun M, Possell M, Adams MA (2020) Impacts of prescribed burning on forest carbon and water. In: *Prescribed Burning in Australasia: The Science, Practice and Politics of Burning the Bush*, eds. Leavesley A, Wouters M, Thornton R. AFAC, 117-123.

CONFERENCE PAPERS

25. Gharun M, Possell M, Bell TL (2017) Modelling feedback between fuel-reduction burning and forest carbon and water balance in Eucalypt forests. Research Proceedings for the Bushfire and Natural Hazards CRC and AFAC Conference. Sydney, Australia.
26. Possell M, Parnell D, Bell TL (2019) Estimating fuel changes with mixture design methodologies. Proceedings for the 6th International Fire Behaviour and Fuels Conference, Sydney. Published by the International Association of Wildland Fire, Missoula, Montana, US.

MILESTONE AND TECHNICAL REPORTS

Research Phase 1 (July 2014-June 2017)

1. Gharun M, Possell M Bell T (2015a) Sampling schema for measurement of the impact of prescribed burning on fuel load, carbon, water and vegetation. Milestone 2.3.2 Final Report, Bushfire and Natural Hazards CRC, 11 p.
2. Gharun M, Possell M Bell T (2015b) Variability in soil and fuel properties at different spatial scales after prescribed burning. Milestone 2.4.2 Final Report, Bushfire and Natural Hazards CRC, 19 p.
3. Gharun M, Possell M, Bell T (2017) Calibration of water balance using digital photography. Milestone 3.4.2 Final Report, Bushfire and Natural Hazards CRC, 21 p.
4. Possell M, Gharun M, Bell T (2016) Application of statistical techniques to Pyrolysis-GS-MS data from soil to identify the impact of fire. Milestone 3.3.2 Final Report, Bushfire and Natural Hazards CRC, 22 p.

Research Phase 2 (July 2017-June 2020)

5. Bell T, Parnell D, Possell M (2018) Sampling and data analysis of field sites in NSW. Milestone 1.4.4 Technical Report, Bushfire and Natural Hazards CRC, 23 p.
6. Bell T, Parnell D, Possell M (2019) Sampling and data analysis of 40 prescribed burns. Milestone 2.4.2 Technical Report, Bushfire and Natural Hazards CRC, 23 p.
7. Parnell D, Bell T, Possell M (2020a) Quantifying the conversion of vegetation to ash for soil carbon fingerprinting. Milestone 2.3.4 Technical Report, Bushfire and Natural Hazards CRC, 23 p.
8. Parnell D, Possell M, Bell T (2020b) Estimating carbon stocks and biomass in surface fuel layers. Milestone 3.1.3 Technical Report, Bushfire and Natural Hazards CRC, 55 p.
9. Parnell D, Bell T, Possell M (2020c) Near infrared spectroscopy as a new fire severity metric. Milestone 3.3.2 Technical Report, Bushfire and Natural Hazards CRC, 31 p.
10. Pepper D, Bell T, Possell M, Parnell D (2020) Model predictions for fuel reduction burning of eucalypt open forest in the Greater Blue Mountains region. Milestone 3.3.1 Technical Report, Bushfire and Natural Hazards CRC, 66 p.
11. Karunaratne S, Possell M, Pepper D, Bell T (2019) Modelling emissions from prescribed burning using FullCAM. Milestone 2.2.3 Technical Report, Bushfire and Natural Hazards CRC, 46 p.
12. Yu M, Pepper D, Bell T, Possell M (2020) Detecting the effects of prescribed burning using generalised additive modelling. Milestone 2.3.3 Technical Report, Bushfire and Natural Hazards CRC, 24 p.

OTHER

Research Phase 1 (July 2014-June 2017)

1. Bell T (2014) Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water and vegetation outcomes. Milestone 1.4.4 Annual Report Y1, Bushfire and Natural Hazards CRC, 3 p.
2. Bell T (2015) Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water and vegetation outcomes. Milestone 2.4.5 Annual Report Y2, Bushfire and Natural Hazards CRC, 17 p.
3. Bell T (2016a) Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water and vegetation outcomes. Milestone 2.4.5 Annual Report Y3, Bushfire and Natural Hazards CRC, 24 p.
4. Bell T (2016b) Advances in forest fire research in Australia. Oral presentation, Environment, Sustainable Agriculture and Forest Management Conference, Padova.
5. Bell T (2017a) Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water and vegetation outcomes. Milestone 4.4.4 Annual Report Y4, Bushfire and Natural Hazards CRC, 23 p.
6. Bell T (2017b) Filter bubbles, wishful thinking and prescribed fires. Keynote presentation, International Congress on Prescribed Fires, Barcelona.
7. Bell T, Kenny B (2014) Optimisation of fuel reduction burning regimes: determining fire size. Milestone 2.1.2 Poster, Bushfire and Natural Hazards CRC.
8. Gharun M, Bell T (2016) Application of computer simulations in Forestry Education. Oral presentation, Environment, Sustainable Agriculture and Forest Management Conference, Padova.
9. Gharun M, Possell M, Bell T (2015a) Spatial variability after prescribed burning: effects on vegetation and soil properties. Milestone 3.1.4 Poster, Bushfire and Natural Hazards CRC.
10. Gharun M, Possell M, Bell T (2015b) Spatial variability in the impact of prescribed burning on the environment in Australian eucalypt forests. Oral presentation, 6th International Wildland Fire Conference, Seoul, South Korea.
11. Gharun M, Possell M, Bell T (2016) Estimation of the impact of fuel-reduction burning on catchment water balance using digital photography. Milestone 4.1.3 Poster, Bushfire and Natural Hazards CRC.
12. Gharun M, Possell M, Bell T (2017) Optimisation of prescribed burning for carbon and water outcomes – an Australian perspective. Oral presentation, International Congress on Prescribed Fires, Barcelona.
13. Possell M, Bell T (2017) Measurement of the combustion properties of selected grasses from central Australia. Oral presentation, International Congress on Prescribed Fires, Barcelona.
14. Raducan G, Silcock D, Arrowsmith C (2016a) An analysis of water quality parameters after bushfires using modelling tools. Oral presentation, 29th Victorian Universities Earth and Environmental Science Conference, Melbourne.
15. Raducan G, Silcock D, Arrowsmith C (2016b) Modelling water quality parameters using eWater, Poster presentation, Fire and Emergency Management Conference (AFAC 2016), Brisbane.
16. Raducan G, Silcock D, Arrowsmith C (2016c) The impact of bushfires on water quality. Oral presentation, Australian and New Zealand Disaster and Emergency Management Conference, Gold Coast.
17. Wang H, Medwell PR, Birzer CH, van Eyk PJ, Tian ZF, Possell M (2015) Investigation of smouldering combustion of biomass fuel. Oral presentation, Australian Combustion Symposium, Melbourne, Victoria.
18. Wang H, van Eyk PJ, Medwell PR, Birzer CH, Tian ZF, Possell M (2017) Analyses of permeability and pressure-drop in south eastern Australian woody debris fuel bed. Oral presentation, International Congress on Prescribed Fires, Barcelona.
19. Yu M, Bishop T, van Ogtrop F (2015) Change detection: effect of wildfire on water quality. Oral presentation, 36th Hydrology and Water Resources Symposium: The Art and Science of Water, Hobart.
20. Yu M, Bishop T, van Ogtrop F, Bell T (2016a) Change detection: effect of wildfire on the water quality of forested catchments. Poster presentation, University of Sydney Faculty of Agricultural Symposium, Sydney, Australia.
21. Yu M, Bishop T, van Ogtrop F, Bell T (2016b) Modelling the effect of wildfire on forested catchment water quality using the SWAT model. Poster presentation, American Geophysical Union Fall Meeting, San Francisco.

Research Phase 2 (July 2017-June 2020)

22. Bell T (2018a) Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water

and vegetation outcomes. Milestone 1.4.6 Annual Report Y5, Bushfire and Natural Hazards CRC, 24 p.
23. Bell T (2018b) Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water and vegetation outcomes. Invited presentation, North American Forest Fire Study Tour, Mt Macedon.
24. Bell T (2019a) Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water and vegetation outcomes. Milestone 2.4.6 Annual Report Y6, Bushfire and Natural Hazards CRC, 29 p.
25. Bell T (2019b) Prescribed burning for multiple objectives – the case for carbon sequestration. Invited presentation, Prescribed Burning – Evidence and Policy Conference, University of Western Australia, Perth.
26. Bell T (2020a) Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water and vegetation outcomes. Milestone 3.4.1 Annual Report Y7, Bushfire and Natural Hazards CRC, 31 p.
27. Bell T (2020b) Prescribed burning for multiple objectives. Invited presentation, National Fire and Fuels Science Forum, an on-line webinar series hosted by the Natural Hazards Cooperative Research Centre and the Australian Academy of Science.
28. Bell T, Adams M, Neumann M, Parnell D, Pepper D, Possell M (2020) Optimisation of fuel reduction burning regimes for fuel reduction, carbon, water and vegetation outcomes. Synthesis Report, Milestone 3.4.1b Bushfire and Natural Hazards CRC, 49 p.
29. Bell TL, Gharun M, Possell M, Adams MA (2018) Can we have it all? Optimal burning regimes for management of fuel, carbon, water and vegetation. Oral presentation, Fire Continuum conference, Missoula.
30. Bell T, Possell M, Gharun, M, Adams M (2020a) Competing for resources after fire – trees need water too. Invited presentation, Putting Lessons into Practice: Reflecting on Water Management in the Face of Fire, Australian National University, Canberra.
31. Bell T, Possell M, Pepper D, Parnell D, Karunaratne S, Yu M, Gharun M, Neumann M, Adams M (2020b) Optimisation of fuel reduction burning regimes for carbon, water and vegetation – an interdisciplinary approach to examine trade-offs between environmental objectives and prescribed burning. Milestone 3.4.5 Poster, Bushfire and Natural Hazards CRC.
32. Karunaratne S, Possell M, Bell T, Pepper D (2019) Modelling carbon emissions from prescribed burning using FullCAM. Milestone 3.1.1 Poster, Bushfire and Natural Hazards CRC.
33. Parnell D, Bell T, Adams M, Possell M (2018) Understanding carbon pools to improve emission estimates from fires. Milestone 2.1.1 Poster, Bushfire and Natural Hazards CRC.
34. Possell M, Gharun M, Adams M, Bell T (2017) Assessing the impact of fire using soil and pyrolysis-GS-MS. Milestone 1.1.1 Poster, Bushfire and Natural Hazards CRC.
35. Taccaliti F, Marzano R, Rizzolo R, Fischetti D, Bell T, Lingua E (2020) New methodology for mapping wildfire risk in the wildland-human interface. Poster presentation, EGU 2020 Virtual Symposium.
36. Gormley AG (2019) *Effects of surface litter by forest classification on fuels and fire behaviour in Hornsby Shire*. Master of Philosophy thesis, University of Sydney, 163 p.
37. Raducan GM (2018) *The impact of bushfires on water quality*. Doctor of Philosophy of thesis, RMIT University, 238 p.
38. Wang H (2018) *Initiation of biomass smouldering combustion*. Doctor of Philosophy of thesis, University of Adelaide, 251 p.
39. Wang H, Tian ZF, Medwell PR, Birzer CH, van Eyk PJ, Possell M (2018) Air permeability of the litter layer in temperate forests of south-east Australia. Oral presentation, 21st Australasian Fluid Mechanics Conference, Adelaide.
40. Yu M (2019) *Approaches for investigating wildfire impacts on catchment hydrology*. Doctor of Philosophy of thesis, University of Sydney, 173 p.
41. Yu M, Bishop T, van Ogtrop F, Bell T (2017a) Assessing SWAT model's sensitivity to fire related changes. Oral presentation, 22nd International Congress on Modelling and Simulation (MODSIM2017), Hobart.
42. Yu M, Bishop T, van Ogtrop F, Bell T (2017b) Change detection: the effect of wildfire on forested catchment water quality: empirical versus mechanistic models. Poster presentation, Fire and Emergency Management Conference (AFAC 2017), Sydney.
43. Yu M, Bishop T, van Ogtrop F, Bell T (2018a) Assessing SWAT model sensitivity to fire-related soil organic carbon changes using digital soil mapping products. Poster presentation, Fire and Emergency Management Conference (AFAC 2018), Perth.
44. Yu M, Bishop T, van Ogtrop F, Bell T (2018b) Digital soil mapping to assess the hydrological impact of wildfire induced changes in SOC. Poster presentation, National Soil Science Conference, Canberra.

PUBLICATIONS IN PREPARATION

1. Adams MA, Buckley TN, Neumann M (202Xb). Get a bigger rake – wildfires highlight climate and policy conundra. *Science* (in preparation)
2. Adams MA, Gharun M, Bell TL (202Xb) Topography controls spatial extent of catastrophic fires in Mountain Ash (*Eucalyptus regnans*) forests. *Global Change Biology* (submitted)
3. Bell TL, Ima H, Parnell D, Possell M (202X) Near infrared spectroscopy as a fire severity metric. *Science of the Total Environment* (in preparation)
4. Neumann M, Adams MA (202X) Better models of wildfire risk: avoiding past errors. *Environmental Research Letters* (in preparation)
5. Neumann M, Turner J, Lewis T, McCaw L, Cook G, Adams MA (202X) Climate and composition determine litterfall and standing litter at continental scale. *Ecosystems* (submitted)
6. Pepper D, Karunaratne S, Possell M, Bell TL (202Xa) Modelling emission from prescribed burning using FullCAM. *Forest Ecology and Management* (in preparation)
7. Pepper D, Possell M, Bell TL (202Xb) A framework for understanding (prescribed) fire events on leaf area and associated ecosystem processes. *Forest Ecology and Management* (in preparation)
8. Pepper D, Possell M, Bell TL (202Xc) Model-data assimilation for prescribed burning of eucalypt open forest in the greater Blue Mountains area. *Forest Ecology and Management* (in preparation)
9. Raducan G, Silcock D, Arrowsmith C (202X) Predicting water quality parameters in Latrobe catchment using eWater source. (submitted)
10. Taccaliti F, Possell M, Dijkstra FA, Adams MA, Bell TL (202X) Carbon and nitrogen fractionation in soil and litter following high and low intensity fire. *International Journal of Wildland Fire* (in preparation)
11. van Meteren S, Parnell D, Possell M, Bell (202X) Reconciling fuel assessment methods – comparing visual and empirical methods. *International Journal of Wildland Fire* (in preparation)
12. Yu M, Pepper D, Possell M, Bell TL (202X) Variation in evapotranspiration in relation to prescribed burning. *Journal of Remote Sensing* (in preparation)

TEAM MEMBERS

The research team operates from two bases, one in New South Wales (University of Sydney) and one in Victoria (Swinburne University). Below is a list of past and present members of the research team.

RESEARCH TEAM AND SUPPORT STAFF

University of Sydney

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INTERNATIONAL VISITORS

Dr Maryna Zharikova, Kherson National Technical University, Ukraine

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Assoc. Prof. Emanuele Lingua, University of Padova, Italy.

END-USERS

End-User organisation	End-User representative	Extent of engagement
Department of Planning, Industry and Environment, NSW (formerly Office of Environment and Heritage NSW)	Max Beukers, Naomi Stephens, Felipe Aires	Representatives from this state government agency have been our main end-users providing continued advice and feedback on research planning, reporting and progress throughout Phase 1 and 2 of research. In Phase 2 of our research, we worked closely with representatives from the Blue Mountains branch of DPIE to shape our research direction and gain access to prescribed burn plans and sites

ACT Parks and Conservation Services, ACT	Neil Cooper, Adam Leavesley	In Phase 1 of our research, we worked closely with representatives of this agency to understand operational requirements and research needs for prescribed burning in the ACT, to coordinate access to field sites and circulate research findings
Forestry Corporation NSW	Tim McGuffog	In Phase 1 of our research, we worked with representatives of this agency to understand their research needs
SA Water	Jacqueline Frizenschaf	In Phase 1 of our research, we worked with representatives of this agency to understand their research needs
Department of Environment, Land, Water and Planning, Victoria (formerly Department of Sustainability and Environment)	Liam Fogarty, Greg McCarthy	In both phases of our research, we worked with representatives from this agency to coordinate access to field sites
NSW Rural Fire Service	Belinda Kenny, Melissa O'Halloran	In Phase 1 of our research, we worked with representatives of this agency to understand their research needs
Department of Parks and Wildlife, Western Australia	Lachlan McCaw, Valerie Densmore	In Phase 2 of our research, we worked with representatives of this agency to understand their research needs
Hornsby Shire Council	Michelle Brown, Amelia Jones	Members of this local agency helped with site information and access for a student research project

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Yu M, Bishop T, van Ogtrop F (2019) Assessment of the decadal impact of wildfire on water quality in forested catchments. Water 11, 533, doi: 10.3390/w11030533

APPENDIX

A1 FUEL LOAD ASSESSMENT – VISUAL *VERSUS* MEASURED

Fuel load was assessed at field sites in Victoria, the ACT and NSW by applying methods currently being used by fire operations (i.e., Hines *et al*., 2010; Gould *et al*., 2011; Watson *et al*., 2012). For sites in Victoria, the ACT and most of the sites in NSW, these data were systematically collected by a single person. This data set provided a unique opportunity to compare estimates of fuel load extrapolated from visual assessment with actual measurements of aboveground biomass, and without the bias that comes with different assessors.

We found that empirical measurements matched indicative fuel loads for less than 50% of our sites, even with a single assessor. Fuel loads were greatly underestimated at low hazard ratings and overestimated at high hazard ratings. This research is currently being prepared for publication (van Meteren *et al*., 202X; see *Publications in preparation*).

Based on our assessment, visual assessment guides should not be relied upon to determine fuel loads as this practice could lead to poor management decisions. However, such guides are useful for describing fuel arrangement and accumulation patterns after fire. It is recommended that visual guides should be adapted for use in different forest types, and visual assessment should be coupled with destructive sampling.

Visual fuel load assessment was poorly matched with measured fuel load. Fuel loads were underestimated at sites with low hazard ratings and overestimated at high hazard ratings.

A2 CALIBRATION OF WATER BALANCE USING DIGITAL PHOTOGRAPHY

A new methodology was validated for estimating the near-surface living biomass from digital images (Macfarlane and Ogden 2012). In this method, foliage cover can be estimated from digital images taken from 50 cm above an area of 50 × 50 cm. For calibration purposes, living material within this area was harvested and biomass was measured. A relationship was established between foliage cover and biomass effectively replacing the need for destructive sampling of near-surface biomass (see Gharun *et al*., 2017 in *Publications list* for details).

A method using digital photography was developed to rapidly quantifying leaf area index of understorey vegetation.

A3 NON-ADDITIVE EFFECTS OF FOREST LITTER ON SURFACE FUEL FLAMMABILITY

Investigation of surface and near-surface fuels formed the basis for a study of flammability of surface fuels (see Gormley, 2019; Gormley *et al*., 2020 in

Publications list). The Simplex Centroid Design method was used to determine optimum mixtures of fuel fractions and a General Blending Model was used to determine the best statistical model fit for flammability metrics (ignitability, combustibility, consumability and sustainability). Flammability measures included time to ignition, burn to completion, vertical fuel height, rate of spread, volume consumed, duration of vertical flame and residual mass fraction. For sites co-located in the Sydney basin representing two distinct types of dry sclerophyll forest, differences in flammability metrics could generally be explained by prevalence of a particular fuel type or dominant overstorey species.

Flammability metrics showed that the flammability of surface fuel can be driven by a single species. The presence of long thin cladodes from *Allocasuarina littoralis* in litter mixtures caused non-additive effects, increasing the rate of flame spread and flame height.

A4 FIRE EASES IMBALANCES OF NITROGEN AND PHOSPHOROUS IN WOOD PLANTS

In contrast to much media reporting and commentary, forest fires in Australia – including prescribed fires and bushfires – are a critically important ecosystem process, without which many of the features that make Australian forests different, and even unique, would disappear. As we showed (see Dijkstra and Adams 2015; Dijkstra *et al*., 2017 in *Publications list* for details), fires do not always cause losses of nutrients. In fact, fires are important to mineralise and release nutrients bound in organic matter that would be otherwise unavailable to plants. Fires can also help rebalance nutrient supplies and offset limitations (e.g., phosphorus limitation is common globally and especially in Australian soils).

Changes in nitrogen and phosphorous content of woody plants and in soil in response to fire may influence the persistence of woody plants in fire-prone ecosystems worldwide.

A5 FIRE EFFECTS ON SOIL PROPERTIES: CASE STUDIES IN SOUTH-EASTERN AUSTRALIA

A Master student research project examined the dynamics of soil nutrients (carbon, nitrogen, phosphorus, nitrate and ammonium) after high intensity bushfire at two locations in central and southern Victoria. Data were obtained by sampling the topmost layer of the soil profile at fine scale resolution (2 cm depth increments to 14 cm depth) immediately and after fire and again at 6 and 12 months.

For all nutrients, greatest availability was in the top 2-4 cm, with concentrations decreasing markedly with depth. Availability of phosphorus and nitrogen (both total and inorganic nitrogen) was greatest for up to 6 months after fire but decreased with time. Soil carbon did not change appreciably over the 12-month sampling period. This research is currently being prepared for publication (Taccaliti *et al*., 202X; see *Publications in preparation*).

Fine scale sampling (e.g., 2 cm depth increments) is needed to detect changes in soil nutrients and carbon after high intensity fire. It is hypothesised that even finer scale sampling (e.g., 1 cm depth increments) would be needed to detect changes after prescribed burning.