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

Annual project report 2018-2019

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University of Sydney & Bushfire and Natural Hazards CRC

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Cover: Prescribed burning at a field site sampled in 2019 in NSW (image from D Parnell).

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EXECUTIVE SUMMARY

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

We have made significant progress in several areas of research over the past 12 months. This has included modelling of carbon emissions from prescribed fires using (a) regression modelling to couple the effect of prescribed fire on water and carbon at a catchment scale, and (b) FullCAM, a process-based model that can track carbon pools in forests systems. The latter is a readily accessible tool that has very good potential to be adopted by End User agencies when required to report on carbon emissions resulting from their efforts to manage fuels. A fuel condition model (the 'litter triangle') detailing carbon load and fuel reduction has been developed for surface fuels in dry sclerophyll forest. This is an easy-to-use tool that can be used as a guide for estimating potential for carbon loss due to prescribed burning. We are in an exciting phase of End User utilisation and tangible uses for our research has been identified and are being pursued.

Reporting on our progress has taken the form of milestone reports, bi-monthly newsletters directed towards our End Users, and presentations for local, national and international forums. We have endeavoured to meet regularly with our primary End User and have established collaborations with research groups such as CSIRO and local land managers from NSW National Parks and Wildlife Service.

Our vision for the next 12 months is to consolidate our research in the area of estimating carbon emissions from prescribed fires, modelling of carbon and water across the landscape for optimisation of planned burning and linking metrics describing combustion of surfaces fuels with fire severity.

END USER STATEMENT

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

Land management agencies such NPWS devote a significant amount of time and capital implementing prescribed burning programs to reduce the overall wildfire risk to life, properties and environmental values. Comparing potential future fire management approaches considering the impacts of prescribed burning to an array of environmental values form the basis of the risk approach being developed by fire managers and scientists across Australia.

Developing knowledge and capacity to predict the effects of prescribed burning on carbon emissions and water resources is vital to assist fire managers for their decision making. This research is helping to develop a better understanding of how fuels are combusted including how carbon is transformed and how water yields from catchments are impacted during prescribed fires at various landscape scales. The modelling tools being developed and tested have potential to be used to forecast how annual and long-term water yield from these catchments, as well as their carbon storage potential, will respond to different treatments.

This project has demonstrated a simple, cost- and time-effective approach to deriving reasonably accurate estimates of carbon emissions from prescribed burning using FullCAM. As a response to important management questions, the research is now trialling the predictive capacity of FullCAM using data collected from sites in the Blue Mountains recently burned by NPWS.

INTRODUCTION

The overall aim of this project is to improve the capability of land managers to use prescribed burning to manage land such that risks of loss of water yield, carbon (C) sequestration capacity and vegetation diversity are mitigated. This project builds on previous research in forested catchments in NSW, the ACT and Victoria that has shown major differences between forest types in effects of fire intensity on subsequent stand and forest hydrology. These differences point to the capability of using different prescribed burning strategies in different parts of catchment landscapes. The project also draws on our research efforts in determining the effect of prescribed burning on C balances in forests in southern Victoria. In effect, this project will define and refine fire management of forests and forested catchments at an appropriate scale. This approach is akin to 'precision land management' that has been developed and used in broadacre agriculture (both cropping and grazing). The key features of this concept are to quantify variability, understand the environment and make sound predictions to continually improve or adapt practices to become more efficient.

A large proportion of the area of south eastern Australia is forested and most of this area is vital for water catchment – for recharge of the Murray Darling Basin, for potable water for capital cities (i.e. Melbourne, Canberra, Sydney) and water for a variety of uses in regional centres and their dependent agricultural communities. The annual and long-term water yield from these catchments, as well as their C storage potential, are amongst the most valuable of natural assets of respective state governments and agencies, including power and water utilities in Victoria, NSW and the ACT.

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 primarily used to govern the timing of prescribed burning. Fire management in Australian forests is also guided by good knowledge of the fire-response traits of key plant species. Similarly, landscape features are well understood in relation to fire – some landscape positions and aspects are more manageable than others, and managers are also able to prioritise prescribed burning on this basis. What has been lacking, but which has become increasingly important, is knowledge and projecting capacity of the effects of prescribed burning on C and water potential (e.g. capacity for C sequestration, water yield and quality) of forests at a manageable spatial scale. This knowledge is required in a format that is readily useable by managers and, most commonly, is delivered in the form of predictive models or tools. To address our current lack of understanding, this project will move research and management capabilities to its next logical focus – building a sensible framework and a predictive model combining and optimising the competing outcomes for prescribed burning.

BACKGROUND

Three underlying problems continue to shape the direction of our project:

1. Limited knowledge of the nature and water storage capacity of soil profiles (e.g. to a depth of at least 1 m) – this hinders both our ability to model water fluxes, especially the yield of water to streams and dams, and our ability to model whole stand and forest water use, before and after fires.

2. Limited capacity to incorporate the dynamics of whole forest growth (i.e. maturity) and tree regrowth after disturbance into relevant models.

3. Limited understanding of the effects of differing fire intensities on soil C. This requires, *a priori*, development of techniques to provide reliable and routine assessment of fire-related temperatures within soils at different depths.

These key issues can be tackled within an overall framework of developing models to facilitate optimisation of prescribed burning regimes. The use of spatially explicit models will consider changes in fuel loads and predict the likely effects of individual fires and collectively as prescribed burning regimes on C and water potentials and vegetation composition.

There is some argument that prescribed fires should be smaller rather than larger, often on the basis that this creates a mosaic of time-since-fire at the landscape scale. What is seldom considered is the heterogeneity within the boundaries of prescribed fires which can include unburnt areas, partially burnt areas, areas burnt at moderate intensity or low intensity. This research is investigating the effectiveness of prescribed fires of different size, as they are currently implemented, in terms of:

- reduction of fuel loads
- C pools
- water quantity
- regrowth of vegetation

Our research is therefore framed with the null hypothesis that the size of fuel reduction fires (e.g. less than 100 ha, greater than 10^3 ha) has no effect on environmental variables or on their effectiveness in fuel reduction. Land managers in Victoria, NSW and the ACT currently implement a number of fuel reduction fires in a typical year (e.g. 20–200 fires), with the size of fires spanning at least two orders of magnitude. These fires provide many opportunities to test this hypothesis.

WHAT HAVE WE BEEN UP TO?

Overall progress

During the past 12 months we have made very good progress and have achieved most of the milestones set for the 2018-2019 period.

The highlights of the year have been:

- Completion of eight milestone reports. Where possible, any final reports are being transformed into manuscripts for submission to peer-reviewed journals for publication.
- Completion of sampling of 100 burn units in dry sclerophyll forests in NSW, ACT and Victoria. The analysis of samples and collation of data has been expertly done by Danica Parnell, our Research Assistant, with some recent assistance from two visiting exchange students. Our sampling efforts will compare actual changes in fuel loads and C losses with these predictions to improve our C modelling understanding and capabilities.
- Informing End Users about the development and efficacy of 'litter triangles' has taken place in a number of reports, newsletters and forums. Predictions of the amount of C and biomass lost from different components of surface fuels (e.g. leaves, twigs, fine fuel, bark) due to prescribed burning has important implications for land managers if they are required to report on emissions from their prescribed burning practices. This research will be fully reported in an upcoming Final Report.
- Our Postdoctoral Researcher, David Pepper, has settled in well and is continuing with planned modelling and prediction work. His efforts have been augmented by the short-term employment of Mengran Yu (from April to October 2019) to calibrate a combined water and C model.
- Recognition of Tina Bell and her contribution to fire ecology in a new journal about science, policy, and technology of vegetation fires (Smith *et al*. 2018).

Research project details

1. Modelling carbon emissions using FullCAM

We have demonstrated a simple, cost- and time-effective approach to deriving reasonably accurate estimates of C emissions from prescribed burning using a widely available model called FullCAM. While we acknowledge that FullCAM has limitations in modelling estimations of C emissions, it has the capacity to track changes in C pools related to fire in forest ecosystems. As FullCAM is used in Australia for the national standard of C accounting, it is subject to continuous ongoing development and improved versions of the model are periodically released through the Department of Environment and Energy. This work has fulfilled Milestones 1.3.2, 1.4.3 and 2.2.3 (see below for descriptions) and is contributing to future Milestones 3.2.2 and 3.3.1. Milestones 1.4.3 and 2.2.3 are being combined and developed into a manuscript intended for peer-reviewed publication.

Using FullCAM, predictions of C emissions were calculated for planned prescribed fires in the Blue Mountains area (Table 1). This exercise required close collaboration with fire planners from the Blue Mountains Branch of NSW National Parks and Wildlife Service in late 2018 and early 2019 to determine their priority burn sites and to gain access to the sites themselves and relevant information about location, vegetation type and timing. Sites were chosen to complement sites we had sampled in previous years and to match the vegetation type we have concentrated on. These sites were sampled in May-July 2019 according to our sampling strategy (Gharun *et al*. 2015) and current work is to determine how closely the predictions match with actually biomass and C losses after prescribed burning. Carbon emissions presented in Table 1 are for sequential prescribed burn and wildfire events on a hectare and whole burn area basis.

Table 1. Predicted carbon (C) emissions using FullCAM for planned prescribed burn sites in the Blue Mountains. Predictions of emissions from prescribed burns are compared to potential emissions from wildfire on a hectare basis (t C ha^{-1}) and for the whole burn area (t C).

Site	Burn area (ha)	Above-ground biomass (t DM ha $^{-1}$)	Prescribed burn (t C ha $^{-1}$)	Wildfire (t C ha $^{-1}$)	Prescribed burn (t C)	Wildfire (t C)
Big Plain	4365	157	0.80	8.96	3479	39097
Lawson Ridge	3303	194	0.75	8.49	2493	28045
Centre Ridge	5217	216	0.84	9.48	4399	49477
Tallara Ridge	375	176	0.69	7.71	257	2891
Porcupine	440	173	0.68	7.60	297	3344
Rocky Waterholes	383	193	0.75	8.45	288	3235
Werombi North	747	186	0.72	8.15	541	6086

Some of the questions put to us by fire managers that we are endeavouring to answer with this research are:

- What is the likely effect of the prescribed burning program on C within each burn block over the short- to medium-term?
- What if we didn't burn? How would the C 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 wildfire. What would be the likely effect of a wildfire on C?

Related milestone reports

Karunaratne S, Possell M, Bell TL (2018) Milestone 1.3.2 Modelling emissions from prescribed burning using FullCAM

Empirical evidence collated over time has shown that prescribed burning can reduce the incidence and intensity of unplanned fires in the Australian landscape (Boer *et al*. 2009). However, due to growing interest in evaluating the environmental impacts of prescribed burning, the importance of assessing C dynamics and estimation of emissions from fires is increasing. Models that are used to estimate emissions from the land sector can be categorised into three broad tiers based on their simplicity, the use of country-specific datasets and parameters and the use of spatially explicit datasets (Penman *et al*. 2003).

The Full Carbon Accounting Model (FullCAM) is a software tool developed by the Australian Government, Department of the Environment and Energy that has been used as a means to report national greenhouse gas dynamics from the land sector due to anthropogenic activities (Department of the Environment and Energy 2016). FullCAM is classified as a Tier 3 model as it provides more accurate and reliable estimates than Tier 1 and 2 models. This model uses spatially explicit, fine resolution soil datasets (e.g. soil C and its fractions) and temporal climatic datasets available at 1 km resolution (Department of the Environment and Energy 2016). Inputs or model drivers within FullCAM can be readily added or adjusted. Changes in C stocks (above- and belowground) and emissions are estimated on a continuous basis (generally at monthly intervals) using non-linear processes that consider interactions among climate, soil and plant growth characteristics and land management activities. This contrasts to linear approaches that are commonly used in Tier 1 and 2 models.

While we acknowledge that FullCAM is not currently able to model all aspects of modelling in terms of C emission estimations, it has the capacity to track C pools related to forest ecosystems. As FullCAM is used for C accounting nationally in Australia it is subject to continuous ongoing development activities and new versions of the model are regularly released through the Department of Environment and Energy. The use of FullCAM by fire and land management agencies will therefore enable them to be compatible with the national standard of C accounting and agencies will be prepared for any C accounting activities that are required in their practice.

Karunaratne S, Possell M, Bell TL (2018) Milestone 1.4.3 Assessing the sensitivity of the key parameters related to fuel reduction burning event within the FullCAM model

The aim of our current research efforts is to assess the usefulness of FullCAM in determining the mass of emissions produced from prescribed burning and use of this tool by fire and land management agencies when planning prescribed burning activities.

Despite changing the default parameter values associated with prescribed burning, the average amounts of C emitted for each site and fuel component used were generally the same. It should be noted that the sensitivity analysis was done by considering one parameter at a time. Use of advanced sampling schemes, such as conditional Latin hypercube, using a greater number of iterations (e.g. n = 1000), and running all parameters simultaneously are recommended for detailed analysis in future.

Sensitivity analysis of the key parameters related to prescribed burning did not report significant variation among C emissions. However, there were differences in model sensitivity among the sites considered due to variation associated with the fuel loads. More complex analyses using a larger data set and more iterations may reveal greater sensitivity.

Karunaratne S, Possell M, Pepper D, Bell TL (2018) Milestone 2.2.3 Modelling emissions from prescribed burning using FullCAM

The Full Carbon Accounting Model (FullCAM) is a software tool developed by the Australian Government, Department of the Environment and Energy as a standard method for C accounting. It is primarily used as a means to report national greenhouse gas dynamics from the land sector due to anthropogenic activities. This study assessed the accuracy and usefulness of FullCAM in determining the mass of C emissions produced from prescribed burning.

FullCAM proved to be a simple and reasonably reliable method for estimating C emissions from prescribed burning activities and for tracking recovery of C pools related to forest ecosystems. In addition, C emissions from different prescribed burning scenarios and from wildfire can be easily compared. The FullCAM model can be used by land managers as a means to manage an important aspect of risk associated with planned burning. If land managers are required to perform C accounting activities in the future, the adoption of FullCAM will enable them to be compatible with the national standard of C accounting.

2. Carbon and water modelling

The C and water modelling project (Milestone 2.3.3) aims to identify the impact of topography, soil and climate on evapotranspiration (ET) after prescribed fire. To investigate this correlation, we have decided to apply regression modelling using data collected from the field combined with satellite-recorded data. Generalised additive models were chosen because of the ability of this technique to handle non-linear, linear and non-monotonic relationships between response and predictor variables. The variables included in the regression model fall into three categories: (1) data collected from the field such as date of ignition of the prescribed burn, location of the prescribed burn and soil structure; (2) remotely sensed variables including vegetation type and normalised difference vegetation index (NDVI), and differences in terrain (elevation, slope and aspect) of the sites; and (3) gridded climate value including rainfall, temperate and solar radiation. Preliminary results have found that, according to MODIS ET (MOD16A2) values for burnt sites compared to unburnt sites, there was a decrease in ET (11.68 mm day^{-1}).

Related milestone reports

Reporting on this milestone is currently overdue but will be completed by Mengran Yu in the form of a draft manuscript for peer-review in October/November 2019.

3. Estimating carbon content of surface fuels

Over the last 12 months, models for estimation of biomass and C load of surface fuels in dry sclerophyll forests have been developed and refined for sites surveyed in NSW, ACT and Victoria. This body of research has been reported in Milestones 2.1.3, 2.2.2, 2.3.4 and 2.4.3 (and as an extended abstract) and will be consolidated into a final report (Milestone 3.1.3) in late 2019. We intend to publish this research in due course.

The three litter fractions used in these models are: (1) fine fuel (<9 mm), (2) leaves, and (3) twigs, bark, fruits and flowers combined into a single component (referred to as 'other'). The C load for each fraction of the surface fuel is the product of its biomass (t ha $^{-1}$) and its measured C content (%). The use of a general blending model (GBM; Brown *et al*. 2015) to create a response surface over varying proportions of these litter fractions has given us the ability to predict the nature of the litter. Using models developed from data collected from unburnt and burnt sites (referred to as 'litter' triangles), we can estimate surface fuel biomass and the C load it represents. The current prediction range that we have for surface fuel biomass is from 8-28 t DM ha $^{-1}$ for unburnt sites and from 0-10.5 t DM ha^{-1} for burnt sites. For estimates of C in surface fuels, the prediction range we have is 3-17 t C ha^{-1} for unburnt sites and 0-5.8 t C ha^{-1} for burnt sites.

To estimate biomass or C load of surface fuel samples from a particular site, the GBM is read in a similar way as a soil texture triangle using the proportions of the three litter fractions as variables. 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 t DM 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 5.5 t DM ha^{-1} of surface fuel remains after prescribed burning. The difference between estimates of biomass and C for unburnt and burnt sites is therefore equivalent to reductions in fuel load and C emissions, respectively.

These models have been further validated by creating 'test' and 'training' data sets. The test data set is used to compare how close the model predictions are to the actual data, or training data set. There were reasonably strong relationships between the model predictions and test data. However, the biomass models for both the unburnt and burnt sites overpredicted by 5% and 11%, respectively. For C, the model for unburnt sites overpredicted by 5% and the model for burnt sites underpredicted by 2%. Further examination of the performance of these models requires testing of predictions against data collected from independent sites. This information will be reported in the future in Milestone 3.1.3.

We are planning to develop and test a single model for biomass and C that is representative of surface fuels from burnt and unburnt dry sclerophyll forests across south eastern Australia. Work is currently being done to collect data from additional sites in NSW to increase the 'boundaries' of our data. Samples have been collected from two low production forests (Stringybark Woodlands and Grassy Box Woodlands) and a high production forest (Blue Gum Forest in the Blue Mountains) to represent surface fuel loads that are not typical of what we have already sampled.

Related milestone reports

Parnell D, Bell TL, Possell M (2018) Milestone 2.1.3 First reiteration of fuel condition/vegetation model – Estimating carbon stocks and biomass in surface fuel layers

While the main intention of prescribed fire is to reduce the risk to life and property, the environmental effects are often overlooked (Sohngen and Haynes 1997;

Butry *et al*. 2001; Fried *et al.* 2004). As planning of prescribed burning becomes more sophisticated and land and fire management agencies become more accountable for their activities, there is a growing need to provide better estimates and predictions of C emissions from burning. The ability to model the C content of individual fractions of the surface fuel layer is important for accurate estimates of C loss due to combustion of biomass. Fractions of surface fuels vary according to environmental factors, topography, climatic conditions, fire intensity and time since fire (Ashton and Chinner 2013; Bailey *et al*. 2015; Fairman *et al*. 2015; Prior *et al*. 2016; Krix and Murray 2018).

Here we describe the first reiteration of a model that can estimate C stocks in surface fuel layers for C accounting purposes. We use empirical data to describe C pools in surface fuels from a range of dry sclerophyll forests in NSW and ACT and use this information to develop an easy-to-use tool to improve emission estimates and predictions.

Parnell D, Bell TL, Possell M (2019) Milestone 2.2.2 Review and test fuel condition/vegetation model – Estimating carbon stocks and biomass in surface fuel layers

In a previous report describing this research, the study area included prescribed burns at four sites in the ACT and nine sites in NSW. This report details modelling done using data collected from an additional seven site located in south eastern Victoria. To understand the potential use for these models, an amalgamated model that consisted of data amassed from Victoria, the ACT and NSW was developed. With the combined model, data points significantly increased the estimate range of C, with a range of 0 to 5.8 t C ha^{-1} for burnt sites and a range of 3 to 17 t C ha^{-1} in unburnt sites. When both burnt and unburnt sites were combined, the model estimated a range of 0 to 8 t C ha^{-1}.

The next report will describe similar response curves for estimation of biomass and the phase of the research will incorporate data from surface litter samples from locations that may improve the spread of data in the models to reduce the need to constrain data when developing response surfaces.

Parnell D, Bell TL, Possell M (2019) Milestone 2.3.2 Draft report/ms fuel condition/vegetation model – Estimating carbon stocks and biomass in surface fuel layers

There are multiple ways to estimate aboveground biomass ranging from relatively simple allometric equations, to highly technical remote sensing technology (e.g. LIDAR) (Ottmar *et al*. 2009; Ottmar 2013; Valbuena *et al.* 2017). These methods require thorough calibration to ensure the best accuracy between observed and prediction data (Valbuena *et al.* 2017). Once aboveground biomass has been satisfactorily characterized and validated, the C content can be calculated according to the type of vegetation and its various components. The C pool may be represented by a single conversion factor (e.g. a value of 47% is used to estimate the C content of surface fuels (IPCC 2004)) or it be more detailed for various fuel fractions (Parnell *et al.* 2018; 2019).

This report contains details of the accuracy of 'biomass response surfaces' before and after prescribed burning and a 'universal biomass response surface' using data combined from sites in the ACT, NSW and Victoria. The models presented in this report have been developed to provide an 'easy-to use' tool to give fire managers the ability to predict changes in surface fuel loads after prescribed burning.

Parnell D, Possell M, Bell TL (2019) Milestone 2.4.3 Calibration fuel condition/vegetation model using field/existing data – Estimating fuel changes with mixture design methodologies

The ability to model the C content of individual fractions in surface fuel layers is important to increase accuracies in estimating C loss due to combustion of biomass. The models presented in this study have used data from sites in dry sclerophyll forests found in ACT, NSW and Victoria and show that, in south-east Australia, unburnt sites have a much greater proportion of twigs and leaves compared to burnt sites, and fine fuel fractions appear to remain similar. The response surfaces fitted to the data based upon the modelling results show reasonable agreement with the data but appear to lack accuracy in regions of the mixture design where data is sparse, or the proportions of a contributing component are either very small (tending towards zero) or very large (tending towards 100%). When the models were tested against data not used in the model development, there were strong relationships between the predictions and the measured data with between an 11% overprediction and a 2% underprediction depending upon what is being modelled. Further examination of the performance of these models requires testing their predictions against data collected from independent sites.

The aim for the final product coming from this research is to provide an easy-to-use tool that will allow land managers to be able to estimate C content in surface fuels before and after a prescribed fire when undertaking routine measurements of fuel loads during pre- and post-fire site assessments. This will allow estimates of the amount of C lost to the atmosphere due to burning to be made.

This report was also presented as part of the International Fire Behaviour and Fuels Conference in Sydney in April-May 2019.

Possell M, Parnell D, Bell TL (2019) Estimating fuel changes with mixture design methodologies. Proceedings for the 6th International Fire Behaviour and Fuels Conference. April 29-May 3, 2019, Sydney, Australia. Published by the International Association of Wildland Fire, Missoula, Montana, USA.

4. Soil carbon fingerprinting

Disturbances such as fires in forest ecosystems can cause changes in C and nutrient pools and imbalances in subsequent C and nutrient cycling. One of the major mechanisms for C and nutrient losses and transformations during fire is combustion of aboveground biomass. A great deal of research has been published about C and nutrient loss from fuels through volatilisation in a range of different ecosystems, but these studies generally only report on losses based on complete combustion. An important step in calculation of C emissions due to prescribed fire is determining the conversion rate of biomass to charcoal and ash as the C may not necessarily be lost to the atmosphere but simply be converted to another form. Understanding the conditions in which C in aboveground biomass is affected by heating and combustion will provide information relevant for post-fire management including better estimates of C loss as emissions and potential for movement of ash due to runoff. There is also an obvious association between fire severity and C and nutrient loss.

To begin research in this area, the first milestone (Milestone 2.1.4; see below) gathered together information from the literature and data we have amassed to better inform our planned laboratory studies. The laboratory-based study has been designed to quantify water, biomass, C and nutrient losses during heating at low temperatures (up to 200°C) and combustion at higher temperatures (>200°C). In time we will link this information to fire severity, a metric readily recognised by fire and land managers.

A pilot study using a set of 'standard' cellulose- or lignin-based materials of different density (i.e. paper, cardboard, plywood) and for a range of weights was created to test combustion conditions in a muffle furnace. It was found that 2-5 g of all types of material burnt consistently when heated at temperatures of 200-600°C. From this information it was decided that three types of surface fuels would be used in the laboratory study (leaves, twigs, bark) with some variation around physical appearance (e.g. size, shape) (Table 2). A standard heating/combustion time of 60 minutes was adopted as this has been used repeatedly in the literature.

Preliminary results, which will be reported more fully in Milestone 2.3.4 (expected to be completed by September 2019), have shown that for the surface fuel materials tested, all size classes of twigs (<0.5, 0.5-1.0, 1.0-1.5 cm diameter) and leaf types (flat, curly and cylindrical (i.e. pine needles)) lost biomass in a consistent pattern (Figure 1). The greatest change in biomass occurs between 200 and 400°C and samples were fully combusted at 500°C. There were some differences among bark type (paperbark, annually-shed thin bark and non-shedding thick bark) with 20% less biomass lost from samples of paperbark burnt at 300°C compared to non-shedding thick bark from Turpentine (*Syncarpia glomulifera*) at the same temperature.

Combustion residues are in the process of being analysed for C and nitrogen content to determine patterns of loss. In addition, assessment of colour changes is being made and near infra-red (NIR) scanning analysis is being tested as a potential method to assess fire severity. Additional testing is being done to determine the effect of timing of heating/combustion (i.e. 5, 15, 30 and 60 minutes) and surface fuel and soil from one of our field sites is also being tested.

Related milestone reports

Parnell D, Possell M, Bell TL (2019) Milestone 2.1.4 Draft report on advances in soil carbon fingerprinting – Quantifying the conversion of vegetation to ash for soil carbon fingerprinting

As fire frequency and extent increases globally, there are emerging uncertainties about how forest ecosystems will respond to the changes associated with more fire in the landscape (e.g. Flannigan *et al*. 2000; Gillett *et al*. 2004; Pitman *et al*. 2007). It is evident that disturbances to forest ecosystems, such as fires, can cause significant changes in C and nutrient pools creating subsequent imbalances in

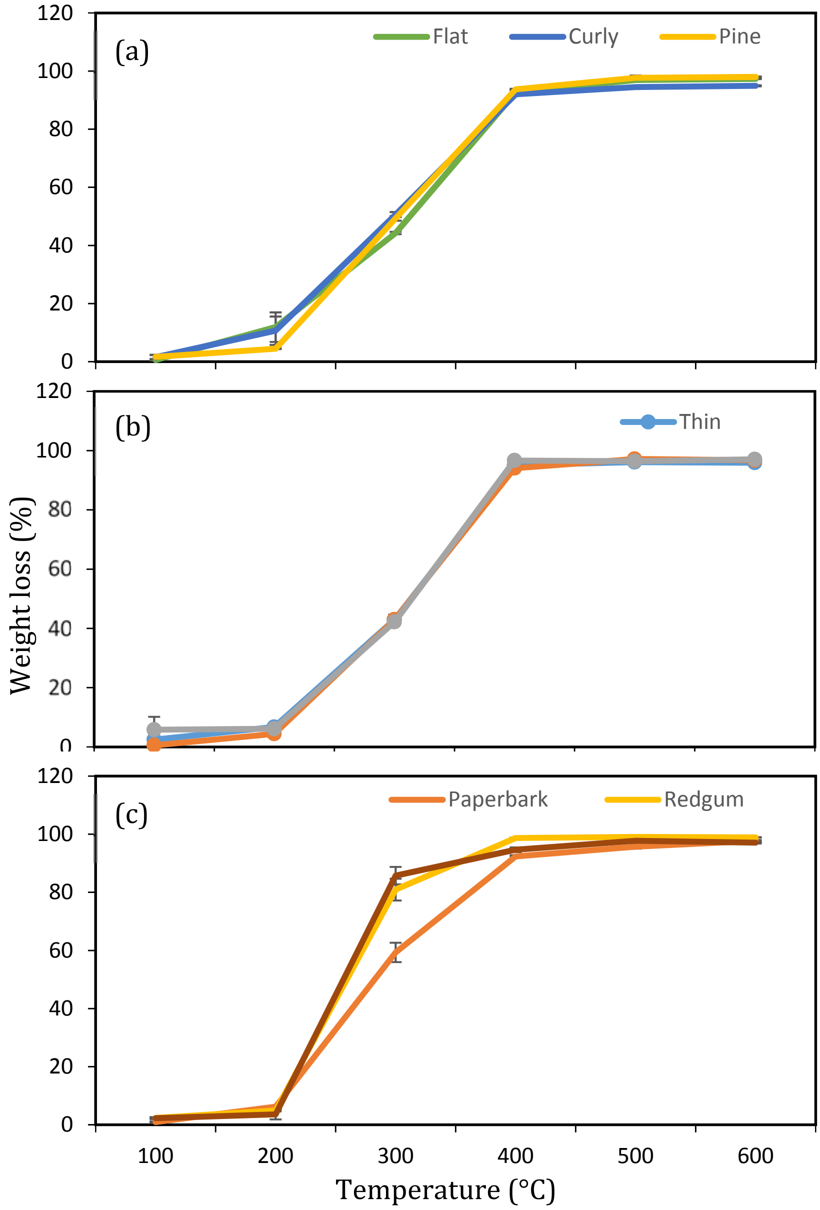
C and nutrient cycling (Pellegrini *et al*. 2018). The main mechanism for C and nutrient losses during fire is heating (volatilisation) and combustion of aboveground biomass. Other losses are due to altered conditions in the post-fire environment (Certini 2005; Caon *et al*. 2014; Butler *et al*. 2017; Zhang and Biswas 2017).

When C losses due to fire are measured or modelled one of the major assumptions made is that fuels, particularly surface and near-surface layers, are completely combusted and removed during fire, irrespective of whether it is a low intensity fuel reduction burn or a high intensity bushfire. This is a common assumption among many studies (Volkova and Weston 2013; 2015; Volkova *et al*. 2015) including our own (Possell *et al*. 2015; Jenkins *et al*. 2016; Gharun *et al*. 2018; Karunaratne *et al*. 2019). However, we know that this is not always the case, as after fire, remaining fuels are in various states of combustion ranging from charred material that is still structurally similar to unburnt fuel, through to ash and charcoal representing near complete combustion. Due to the heterogenous nature of fire, patches of fuel may even remain unchanged. Consequently, a call for more research to determine rates of formation of pyrogenic C and subsequent turnover rates was recently made (Volkova *et al*. 2019). The research we are currently doing aims to develop a greater understanding of how fuels are combusted and the transformation of C pools during prescribed fire.

Table 2. Collection location, species and descriptions of surface fuel samples collected for the soil carbon fingerprinting study.

Category	Collection location	Species	Description
Leaves	Richmond	*Eucalyptus saligna*	Curly leaves
Leaves	Hornsby	Mixed *Angophora costata, Eucalyptus saligna, Syncarpia glomulifera*	Flat leaves
Leaves	Camden	*Pinus radiata*	Cylindrical leaves
Cladodes	Eveleigh	*Allocasuarina cunninghamiana*	Cylindrical 'leaves'
Twigs	Hornsby	Mixed *Angophora costata, Eucalyptus saligna, Syncarpia glomulifera*	0-2.5 mm
Twigs	Hornsby	Mixed *Angophora costata, Eucalyptus saligna, Syncarpia glomulifera*	2.5-5.0 mm
Twigs	Hornsby	Mixed *Angophora costata, Eucalyptus saligna, Syncarpia glomulifera*	>5.0 mm
Bark	Eveleigh	*Melaleuca quinquenervia*	Paperbark
Bark	Hornsby	*Angophora costata*	Annually-shed thin bark
Bark	Hornsby	*Eucalyptus saligna*	Annually-shed thin bark
Bark	Hornsby	*Syncarpia glomulifera*	Non-shedding thick bark

Figure 1. Biomass loss (%) of three types of surface fuels; (a) leaves, (b) twigs and (c) bark during heating and combustion. Points represent mean values ± standard error (n = 8 per fuel type and temperature).



5. Sampling and data analysis of prescribed fires

An additional 40 'burn units' have been sampled during the past 12 months to suit the requirements of our various areas of study. This brings our total sampling effort to 100 burn units (Table 3). As a reminder, a burn unit is a pair of sites that are measured and compared. The pair of sites can be in adjacent burnt and unburnt areas and sampled at the same time (referred to as 'burnt' and 'unburnt' plots or the same site but sampled at different times (referred to as 'pre-fire' and 'post-fire' plots). To supplement our studies for development of the fuel condition/vegetation model, some of our sampling efforts have only included unburnt plots due to requirements of specific vegetation types where burnt representatives could not be found.

Table 3. Details of 100+ burn units sampled throughout the project. Burn units (paired sites sampled before/after fire or in adjacent unburnt/burnt areas) feature for burn units numbered 1-78 and as unburnt plots only for units numbered 79-106.

Burn unit number	Burn/site name	Condition	Sampling/ resampling date
VICTORIA			
1-3	Frogs Hollow	Pre-/post-fire	March 2011/January 2015
4-6	Upper Tambo	Pre-/post-fire	February 2011/January 2015
7-9	Poddy	Pre-/post-fire	March 2011/January 2015
10-12	South Boundary	Pre-/post-fire	March 2011/January 2015
13-15	Sandy Point	Pre-/post-fire	February 2011/January 2015
16-18	Oliver	Pre-/post-fire	April 2012/January 2015
19-21	Gravel	Pre-/post-fire	March 2012/January 2015
22-24	Patrol	Pre-/post-fire	April 2013/January 2015
25-27	Pettmans	Pre-/post-fire	March 2013/January 2015
ACT			
28-30	Googong	Unburnt/burnt	April 2015
31-33	Tidbinbilla	Unburnt/burnt	April 2015
34-36	Wrights Hill	Unburnt/burnt	April 2015
37-39	Cotter	Unburnt/burnt	May 2015
NSW			
40-42	Haycock Trig	Unburnt/burnt	September 2015
43-45	Helicopter Spur	Unburnt/burnt	September 2015
46-48	Spring Gully	Unburnt/burnt	September 2015
49-51	Paterson	Unburnt/burnt	October 2015
52-54	Lakesland	Unburnt/burnt	October 2105
55-57	Martins Creek	Unburnt/burnt	April 2016
58-60	Joadja	Unburnt/burnt	April 2016
61-63	Kief Trig	Unburnt/burnt	May 2016
64-66	Left Arm	Unburnt/burnt	May 2016
67-69	Rocky Waterholes	Unburnt/burnt	May 2019
70-72	Lawsons Ridge	Unburnt/burnt	June 2019
73-75	Belmore Crossing	Unburnt/burnt	June 2019
76-78	Oak Ridge	Unburnt/burnt	June 2019
Surface fuel sampling only			
79-83	Wombat 1-5	Unburnt	August 2018 to August 2019
84-88	Orbost 1-5	Unburnt	August 2018 to August 2019
89-91	Arcadia 1-3	Unburnt	September 2016
92-94	Halls Creek 1-3	Unburnt	2016
95-97	Booker Road 1-3	Unburnt	2018
98-100	Whitecross Road 1-3	Unburnt	2018
101-103	Stringybark Woodland 1-3	Unburnt	2018
104-106	Grassy Box Woodland 1-3	Unburnt	2018

Communication

We presented our project formally to End Users on several occasions including:

1. Malcolm Possell and Tina Bell presented research related to the efficacy of modelling emissions from fires using FullCAM at the Research Advisory Forum in Brisbane in November 2018.

2. Malcolm Possell presented our recent work at the 6th International Fire Behaviour and Fuels Conference held by the International Association of

Wildfire Conference in Sydney in April-May 2019. His presentation was titled *Estimating Fuel Changes with Mixture Design Methodologies*.

3. Malcolm Possell and David Pepper presented a research update at the Research Utilisation Forum in Darwin in late April 2019.

More focused meetings were also held throughout the last 12 months:

4. To get back on track after significant delays in the first half of 2018, Malcolm Possell, Senani Karunaratne and Tina Bell met with Felipe Aires, our End User from the Department of Planning, Industry and Environment (DPIE), NSW, and John Bates in August 2018 to discuss progress and milestone variations. The resulting documentation has become the blueprint for significant progress during the past 12 months.

5. To promote End User translation, Malcolm Possell, Senani Karunaratne and Felipe Aires met with David Taylor, a Senior Operational Fire Planner in the Blue Mountains District, in mid-2018 to investigate the potential for using FullCAM for prediction emissions from prescribed burning. Subsequent contact with David Taylor has resulted in selection and sampling of field sites this year.

6. Senani Karunaratne and Tina Bell attended the annual AFAC/BNH CRC conference in Perth in September 2018. Meetings were organised with End Users from WA, SA and ACT for discussions to investigate the potential for using FullCAM for prediction emissions from prescribed burning.

7. Malcolm Possell, Senani Karunaratne and Tina Bell met with Dr Keryn Paul from CSIRO about sharing data and forming a collaboration based on the use of FullCAM in prescribed burning. David Pepper has been remained in contact with the research group from CSIRO for advice and feedback related to the use of FullCAM.

We have also presented our research to several other audiences:

1. Tina Bell presented about C and water research to the North American Forest Fire Study Tour group in Mt Macedon, Victoria in September 2018.

2. In December 2018, Tina Bell met with fire researchers, Prof. Budi Indra Setiawan from the Ministry of Agriculture, The Republic of Indonesia, based in Jakarta, and Ms Wirastuti Widyatmanti, Researcher in the Cartographic, Remote Sensing and GIS Study Program at Gadjah Mada University, Yogyakarta about potential collaborations involving fire research in Indonesia.

3. Invitation to submit a commentary to a planned book titled: *Prescribed Burning in Australasia – The Science and Politics of Burning the Bush* (eds. A Leavesley, M Wouters, R Thornton). Our submission has been accepted and is titled: Impacts of prescribed burning on forest C and water (Bell TL, Gharun M, Possell M, Adams MA).

To improve communication, a short newsletter has been circulated to End Users since June 2018. These newsletters have contained information about research being done by our group. In the last year, bi-monthly editions of the newsletter have provided updates about student research and project updates. Future editions of the newsletter will feature results from Dr Mengran Yu's PhD research (August 2019) and current student research projects (October and December 2019).

What are we up to next?

In the next 12 months we are aiming to achieve the following tasks and objectives:

- Completion of analysis of all samples collected from field sites in 2019. This data will be collated and used for testing models developed for testing of greenhouse gas emissions (i.e. predictive modelling using FullCAM and regression modelling for C and water) and for the fuel condition/vegetation model (referred to as the 'litter triangle').
- Extend modelling capabilities by testing models on data provided for additional vegetation types from Western Australia (e.g. *Banksia* woodland and Jarrah (*Eucalyptus marginata*) forests) in collaboration with land managers and researchers from DPAW.
- Complete current work related to soil C fingerprinting and initiate new related research investigating the potential to: (a) use near infra-red spectroscopy of combustion residues to determine fire intensity, (b) detect soil C change after fire from satellite imagery, and (c) interrogate fire severity maps with patterns of heterogeneity of surface fuel combustion.
- Continue research related to fuel flammability 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.
- Work closely with End User agencies to translate our research into practice and provide training for model use and interpretation, particularly by providing training for use of FullCAM for C accounting.

Postgraduate student research

Mengran Yu – Approaches for investigating wildfire impacts on catchment hydrology

PhD passed in June 2019, enrolled at the University of Sydney; scholarship funded by BNH CRC.

Thesis abstract

Wildfire has serious impacts on the hydrological cycle and water quality of forested catchments. Forested catchments are commonly used as an important source of drinking water supply in Australia and internationally. Monitoring short-term and long-term post-wildfire catchment hydrology (water quantity and quality) change is important for catchment management. Past studies are limited by data availability and method used. In this thesis, we firstly used empirical (linear mixed model and k-mean clustering) and physical-based hydrological model – Soil and Water Assessment Tool (SWAT) to detect the effect of wildfire on forested catchment hydrology and then built scenarios using physical-based model to investigate the cause of the catchment hydrology change and identify the wildfire sensitive areas in catchments for catchment protection. The case study used here is the 2001/2002 Sydney wildfire, 10 years of pre-wildfire and 10 years of post-wildfire water quantity and quality data were collected by WaterNSW and used in this study.

We have successfully used linear mixed model and SWAT to detect the wildfire effect on catchment hydrology in the thesis. As a result, the empirical model observed a long-term (5-10 years) post-wildfire water quality change; this change is more considerable during post-wildfire event period. The result from physical-based hydrological models also indicated a long-term change in total suspended sediments concentration during post-wildfire period. In addition to the change detected. Our scenario in physical-based models also observed that post-wildfire soil carbon change has limited effect on catchment hydrology and vegetation change is the main cause of post-wildfire catchment hydrological change. Out models also suggested that sub-catchments with higher slope increases, shorter slope, and smaller soil top layer bulk density, clay, and carbon content, are the most wildfire sensitive areas and should be protected the most.

Yu M, Bishop T, Van Ogtrop F (2018) Assessment of the decadal impact of wildfire on water quality in forested catchments. *Water* 11, 533. https://doi.org/10.3390/w11030533

Angela Gormley – Effects of surface litter by forest classification on fuels and fire behaviour in Hornsby Shire

MSc passed in April 2019; enrolled part-time at the University of Sydney; Associate Student of BNH CRC.

Thesis abstract

Globally, bushfires are an ecological phenomenon that can cause deaths and widespread destruction of assets such as homes, utilities and essential infrastructure. Bushfires usually start in forest litter on a forest floor. The research described in this thesis used empirical data to characterise the physical and chemical attributes of litter, a component of forest and woodland fuels that is particularly important for propagation of fire. Differences in the amounts, arrangement and flammability of components of litter were determined for Sydney Coastal Dry Sclerophyll Forest, a common vegetation type in the Sydney basin. Surface litter was investigated at study sites at Rofe Park, Hornsby Heights and Halls Creek, Arcadia, New South Wales, Australia.

Data describing fuel load, structure and condition of surface litter were gathered using semi- quantitative (fuel hazard score, percent cover score, pin transect) and quantitative methods (surface litter depth, bulk density and soil moisture).

These methods indicated both the Halls Creek and Rofe Park sites had ladder fuels with an extreme risk of fire. Rofe Park was a wetter site with higher nitrogen values because *Allocasuarina littoralis* was only found there. However, these physical and chemical measurements do not inform about flammability of surface litter from these sites. Surface litter was sorted into fractions (e.g. whole leaves and twigs, partially and fully decomposed organic material) and used to determine which component or mixture of components were the most flammable. 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. Both sites had rapid time to ignition measurements.

Although, 60% of Halls Creek samples failed to burn versus 30% of Rofe Park mixtures, samples from Rofe Park were more flammable than Halls Creek because of vertical flame heights that were twice as high and rate of spreads that were twice as rapid. *Allocasuarina littoralis* provided a non-additive effect by driving flammability of Rofe Park litter mixtures. Halls Creek samples had negative and positive non-additive effects affecting three flammability metrics; bulk density, residual mass fraction and rate of spread. Samples from Rofe Park had strong positive non-additive effects of six flammability metrics; burn to completion, residual mass fraction, rate of spread, volume consumed, vertical fuel height and duration of vertical flame. *Allocasuarina littoralis* was the most flammable component overall. Twigs were the most flammable component in the litter from Halls Creek.

Chemical analyses of litter fractions included total carbon and nitrogen. The carbon values were similar but there was a significant difference in nitrogen values possibly because the nitrogen-fixing species *A. littoralis* was found at Rofe Park.

The flammability data were optimised to find the maximum or minimum fit for the Simplex Centroid Design. These optimisations demonstrated the ideal litter mixtures from both sites that produce the maximum and minimum flammability for all flammability metrics. Knowledge about fuel flammability of litter from sites with the same fire prone vegetation type will help inform management decisions about prioritising mitigation of fire risk. As a result, land managers can benefit from information about fuel loads and flammability. This experimental methodology can be used for other forest types as well.

Draft manuscript: Gormley AG, Bell TL, Possell M (2019) Non-additive effects of Sydney Coastal Dry Sclerophyll Forest litter on flammability. *Fire*. www.mdpi.com/journal/fire

Veronica Quintanilla – Dynamics of litterfall and fine fuels after fire in sclerophyll forests and woodlands

PhD commenced July 2017; enrolled at the University of Sydney; Associate Student of BNH CRC, co-supervised by Tina Bell, Mark Adams and Feike Dijkstra.

During the past 12 months Veronica has completed the following:

- Bi-monthly litterfall collections have been made at two study sites in Victoria (Orbost and Wombat). Sixty samples were collected at each location making a total of 120 per collection. On return to the laboratory, the samples are oven-dried, sorted into different categories (leaves, bark, fruits and twigs) and weighed to estimate forest productivity at the different locations.

- A full year of litterfall samples will have been collected and processed by August 2019. The next step will be to investigate variations in patterns of litterfall (productivity) based on topographic aspect and relative location (ridge, mid-slope and valley bottom).

- Attended the IAWF Conference held in Sydney in April/May 2019 and the NSW Bushfire Risk Management Research Hub Conference in Sydney in June 2019.

Zhihan Michelle Wang – Ashes to ashes: the nature of ash produced from wildfires

This study will focus on the amount of carbon and nitrogen lost through volatilization and combustion with controlled heating and burning of material typically burnt during a bushfire (e.g. leaves, twigs, bark, decomposing material, surface soil). After heating and burning, the change in biomass, colour, pH, EC and particle size of ash will also be examined. Currently, there are only a few studies that describe physical changes in fuel after being burnt, such as ash colour and particle size difference, but little other change has been quantified. This study will therefore add to the small but growing body of knowledge about the conversion of forest fuel to ash. This project will also contribute to ongoing research into determining C emissions from fires, and the physical and chemical features of the diverse fuel types.

Matthias Geising – Ashes to ashes: the nature of ash produced from wildfires

Matthias is an international exchange student from Bielefeld University, Germany who has recently completed a Bachelor of Environmental Sciences. He was awarded a 12-week DAAD scholarship to participate in an internship program to do laboratory-based research, learn analytical techniques, experience the research culture at an Australian university, and to improve his English written and oral language skills. His project will be done from June-August 2019 and will involve laboratory-based combustion studies of the change in biomass and carbon and nitrogen content of three types of surface fuel (bark, leaves and fine fuel) over time (5, 15, 30 and 60 minutes heating) and temperature (25, 100, 200, 300, 400 and 500°C). This project complements work done by another student and will add information to one of our current milestones relating to

Marisa Estefania González Pérez – Flammability of dry sclerophyll forest litter

Marisa is an international exchange student from the Universidad Nacional Autónoma de México, Mexico. During her 12-week visit (June-August 2019), Marisa will be measuring the flammability of leaf litter collected from dry sclerophyll forests and determining the accuracy of some recently developed empirical models in predicting flammability metrics (Gormley 2019).

Marc Manzoni – Germination potential of native plant species

This project will investigate the germination requirements of five native Australian species: Warrigal Greens (*Tetragonia tetragonoides*), Bush Tomato (*Solanum chippendalei*), Purslane (*Portulaca oleracea*), Native Millet (*Panicum decompositum*) and Kangaroo Grass (*Themeda triandra*). All of these species have the potential to be grown *en masse* as an agricultural enterprise as part of the developing native food industry. Native seeds cannot be treated the same as their domesticated counterparts and they all require distinct individualised treatment for collection, cleaning, storage and germination. There would considerable benefit greatly from a single seed treatment that can be used on multiple species to significantly increase seed germination rate. Literature on germination requirements for these species range from the effects of fire such as smoke and ash, dry heat, wet heat (boiling water), light, abrasion, stratification, fire, fermentation and the replication of diurnal temperatures – the difference between the daily maximum and minimum temperature. Most studies have only tested one or two variables for germination, this project aims to test a number of variables to investigate the potential for a single 'multi-treatment' that could effectively promote germination in a large range of native species.

TEAM MEMBERS

The research team operates from two bases, one in New South Wales (University of Sydney) and one in Victoria (Swinburne University). The division of research and outputs are reflected in current and future milestones.

Researchers and support staff

University of Sydney

Assoc. Prof. Tina Bell (Project Leader)

Assoc. Prof. Feike Dijkstra (Researcher)

Ms Danica Parnell (Research Assistant)

Dr David Pepper (Postdoctoral Fellow, Landscape Modelling)

Dr Malcolm Possell (Researcher)

Dr Mengran Yu (Postdoctoral Fellow, Landscape Modelling)

Mr Michael Turner (Technical Officer)

Swinburne University of Technology

Prof. Mark Adams (Researcher)

Dr Majid Shadman (Postdoctoral Fellow, Geomatics)

Past researchers and support staff

Dr Mana Gharun (Postdoctoral Fellow)

Ms Ariana Iaconis (Research Assistant)

Dr Senani Karunaratne (Postdoctoral Fellow)

Current research students

Mr Matthias Geising, international exchange student, Bielefeld University

Ms Marisa Estefania González Pérez, international exchange student, Universidad Nacional Autonoma De Mexico

Mr Marc Manzoni, Honours candidate, University of Sydney

Ms Veronica Quintanilla, PhD candidate, University of Sydney

Ms Zhihan Michelle Wang, Honours candidate, University of Sydney

Graduated research students

Ms Angela Gormley, MSc candidate, University of Sydney

Dr Gabriella Raducan, PhD candidate, RMIT

Mr Flavio Taccaliti, MSc candidate, University of Padova, Italy

Ms Sophie van Meteren, MSc candidate, University of Lorraine, France

Dr Houzhi Wang, PhD candidate, University of Adelaide

Dr Mengran Yu, PhD candidate, University of Sydney

End Users

Naomi Stephens and Felipe Aires, Department of Planning, Industry and Environment, NSW

Adam Leavesley, ACT Parks and Conservation Services, ACT

Mark Lutz and Greg McCarthy, Department of Environment, Land, Water and Planning, Victoria

Tim McGuffog, Forestry Corporation NSW

Jacqueline Frizenschaf, SA Water

Melissa O'Halloran, NSW Rural Fire Service

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