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

Annual report 2019-2020

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Cover: Approach to a field site in the Blue Mountains, NSW. Source: D Parnell.

TABLE OF CONTENTS

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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, for continued support and faith in our capabilities.

EXECUTIVE SUMMARY

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

We have made good progress over the past 12 months and have completed a number of milestones. Fieldwork and analysis of associated samples has ben completed and the data sets generated have formed the basis of our modelling efforts. Research has included: (i) landscape-scale modelling of the effect of prescribed burning on evapotranspiration as the main driver for water use by vegetation; (ii) calibration and testing of FullCAM, a process-based model that can track carbon pools in forests systems, that we have shown is sensitive enough to integrate changes due to prescribed burning; (iii) testing of a fine fuel model that can be used to determine changes in biomass (fuel load) and carbon content in surface fuels without laborious sample collection and analysis; and (iv) use of near infrared spectroscopy to determine fire intensity and severity.

Modelling using FullCAM and the fine fuel model are tools that have very good potential to be adopted by end-user agencies when required to report on carbon emissions resulting from their efforts to manage fuels. For example, the fine fuel model is an easy-to-use tool that can be used as a guide for estimating potential for carbon loss due to prescribed burning. Our recent advances with near infrared spectroscopy of fire residues suggests that the next steps will be to move from a laboratory setting to the field to test the efficacy of hand-held devices. The potential to develop a simple, yet accurate method for determining fire intensity would aid in ground-truthing of fires to replace current methods that are mostly subjective.

Reporting on our progress has taken the form of milestone reports (draft reports and Technical Reports), bi-monthly newsletters directed towards our end-users, and presentations for local, national and international audiences. We have endeavoured to meet regularly with our primary end-user and have continued collaborations with research groups such as CSIRO and local land managers from NSW National Parks and Wildlife Service. As our project ends, we will produce a synthesis of our research and will develop it further for peer-review publications.

END-USER PROJECT IMPACT STATEMENT

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

Land management agencies need evidence-based science to support decision making processes such as placement, prioritisation and optimisation of prescribed burns. Currently, there is a gap in knowledge for projecting the effects of prescribed burning on carbon and water of forests at manageable spatial scales. Addressing this knowledge gap is essential for land managers to generate robust processes where these types of decisions are required.

This project worked on a range of areas to generate models to improve our understanding and capacity to predict changes in carbon and water in forests affected by prescribed fires. Efforts using empirical data in FullCAM showed that the model can be useful to predict the effects of prescribed burning on carbon. However, for outputs to be more useful and accurate, additional data describing structural pools of carbon and how these pools can be partitioned is recommended. Regardless of improvements in data sets, there are still many assumptions that need to be taken in consideration. It would therefore be useful for the research team to work with the developers of FullCAM at CSIRO to make some adjustments that would make the model more amenable for application to prescribed burning. At present it appears that FullCAM would be better used as an investigative research tool rather than for strategic or operational fire management applications.

The surface fine fuel model developed in this project is an easy-to-use tool that can be used as a guide for estimating potential for carbon loss due to prescribed burning. This tool has potential to be further tested and developed in future initiatives. Additionally, advances with near infrared spectroscopy of fire residues suggests that the next steps will be to move from a laboratory setting to the field to test the efficacy of hand-held devices. The potential to develop a simple, yet accurate method for determining fire intensity would aid in ground-truthing of fires to replace current methods that are currently mostly subjective.

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, loss of carbon (C) sequestration capacity and loss of vegetation diversity are recognised and, where possible, minimised. This project builds on a body of research in forested catchments in NSW, the ACT and Victoria that has shown differences between 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; Gharun et al., 2018). Consequently, prescribed burning may be appropriate in some parts of the landscape and individual catchments but not others.

The project also draws on our previous research efforts in determining the effect of prescribed burning on C balances in forests in southern Victoria (Jenkins et al., 2014; 2016; Turnbull et al., 2014; Possell et al., 2015). To improve our knowledge of strategic burning and reduce risk we seek to quantify variability in forests and fuels in eastern Australia, and better understand the processes involved in C and nutrient cycles to make sound predictions to continually improve the efficacy of 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 the 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 knowledge and a capacity for projecting the effects of prescribed burning on the C (e.g. capacity for fuel accumulation and C sequestration) and 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 of prescribed burning.

BACKGROUND

Three underlying key issues continued to shape the direction of our project:

1. Limited knowledge of the nature of soil profiles (e.g. to a depth of a t least 1m) and its water storage capacity – 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. Limted understanding of the effects of differening 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.

During this project, these key issues have been tackled within an overall framework of developing methods to facilitate optimisation of prescribed burning regimes (Gharun et al., 2017a). The use of spatially explicit models considers changes in fuel loads and can predict the likely effects of individual fires and collectively as prescribed burning regimes on C and water dynamics and vegetation composition.

Some argue 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, however, is the heterogeneity within the boundaries of prescribed fires which can include unburnt areas, partially burnt areas, and areas burnt at moderate or low intensity. This research investigated the effectiveness of prescribed fires of different size and position in the landscape, as they are currently implemented, in terms of:

- reduction of surface and near-surface fuel loads
- C pools, particularly in surface and near-surface fuels
- predicting change in water quantity
- regrowth of vegetation.

Our research has been framed with the null hypothesis that the size of prescribed fires (e.g. less than 100 ha, greater than 103 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 have provided many opportunities to test this hypothesis.

RESEARCH APPROACH

The emphasisof our research has been to increase knowledge about the effect of prescribed burning on three important environmental elements – vegetation (fuels), water and C. As such, the main aim has been to develop and/or test spatially explicit models combining existing and new models of fuel dynamics, C balance, catchment hydrology, nutrient cycling and biomass accumulation. To achieve this, the project had the ambitious goal of sampling 100 burn units to acquire empirical data to test existing 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 will be described in the following section.

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

Together with nine sites (27 burn units) previously sampled in Victoria, 13 sites (39 burn units) were sampled in NSW and the ACT during the first phase of research (July 2014-June 2017) (Figure 1a). Data from these sites were used to explore temporal and spatial variation in vegetation/fuel after disturbance. In the second phase of research (July 2017-June 2020) another 12 burn units were sampled (Figure 1b). In this research, sampling efforts were refocussed, 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.

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

- 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?

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

We measured a range of vegetation (fuel) and soil properties in relation to prescribed burning in a consistent and systematic way (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 C and total nitrogen (N).

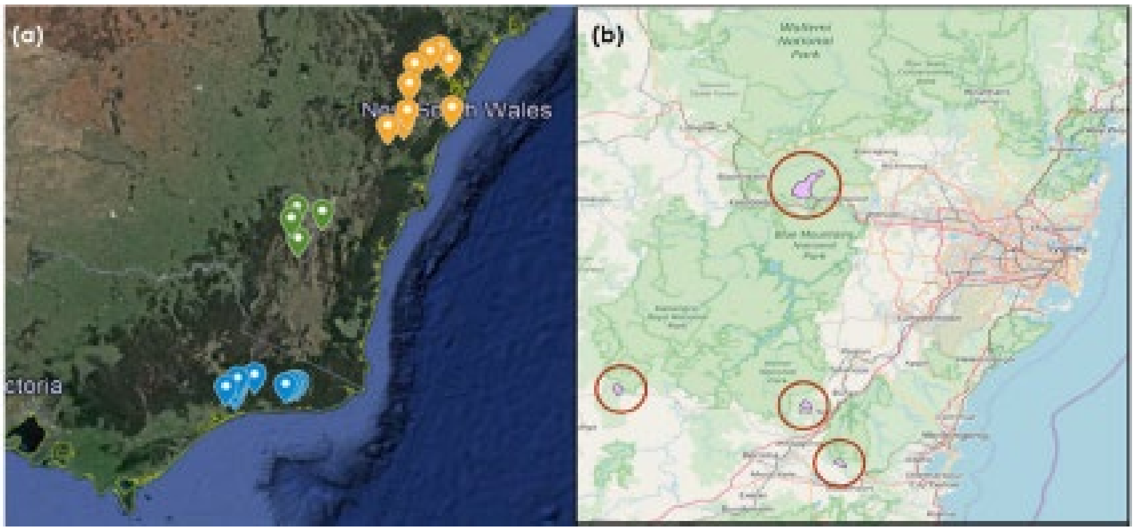

FIGURE 1. SITES SAMPLED IN DRY SCHLEROPHYLL FOREST IN EASTERN AUSTRALIA: 12 BURN UNITS IN THE ACT, 27 BURN UNITS IN NSW AND 27 BURN UNITS IN VICTORIA. SITES SAMPLED IN THE BLUE MOUNTAINS IN 2019 HAD A TOTAL OF 12 BURN UNITS.

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 Sydney Coastal Dry Sclerophyll Forest at elevations less than 700 m and Sydney Montane 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 MILESTONES FOR 2019-2020

During the past 12 months we have made very good progress and have achieved all of the milestones set for the July 2019-June 2020 period.

The highlights of the year have been:

- Completion of field sampling, data collection and samply analysis
- Completion of 25 research and administrative milestones

The key milestones presented as final reports are described below.

FIELD SITES AND SAMPLE ANALYSIS

Milestone 2.4.2 Report on sampling and data analysis of 40 FRFs – Sampling and data analysis of 40 prescribed burns (September 2019, Bell T, Parnell D, Possell M)

This milestone provides details of the remaining field sites used to achieve the goal of sampling and analysing 100 burn units. Fieldwork was finalised in the July-September 2019 quarter with a final sample collection from Oak Ridge in the Blue Mountains. In the following quarter (October-December 2019), basic site information (i.e. DBH, height of overstorey and understorey, total litter biomass, CWD diameter and length) for sites sampled in the Blue Mountains (12 burn units) were collated and reported as part of this milestone. These data have been used to test the ability of an existing model, FullCAM, to detect changes in C due to prescribed burning (see Milestones 3.2.2 and 3.3.1).

Additional sites (e.g. low and high productivity sites) were specifically selected to test a new model developed for predicting changes in biomass and C with prescribed burning without end-users having to undertake laborious sampling and analysis (see Milestone 3.1.3). We have also used samples from field sites described in this report to explore the potential for determining fire intensity and severity using near infra-red spectroscopy (see Milestone 3.3.2).

Laboratory analysis during the course of the past 12 months has included litter sorting, weighing and analysis of C and N of each fraction. Additional surface and elevated fuel samples from one of the sites in the Blue Mountains were used to create char and ash samples and were analysed for C and N. This research is continuing as part of an undergraduate research project in 2020.

MODELLING CARBON AND WATER

Milestone 2.3.3 Calibration of water and carbon model using field/existing data (April 2020, Yu M, Pepper D, Bell T, Possell M)

Prescribed fire mostly affects the understorey vegetation and, therefore, impacts forest ecosystems differently compared to bushfires. Evapotranspiration (ET) is a strong indicator of a change in forest hydrology and is directly affected by removal of vegetation. The research presented in this report aimed to determine the effect of prescribed fire on forest evapotranspiration (ET), the sensitivity of ET to difference in climate and terrain, and difference between sites in NSW/ACT and Victoria.

Empirical data collected from field sites in Victoria and NSW were used to test whether a simple modelling technique – generalised additive model (GAM) – could be used in conjunction with satellite imagery to detect the effect of prescribed burning on the hydrological cycle. Variables included in the ET GAM were site details (location, elevation, aspect, slope), soil properties (total C and N), 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 together.

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, short-term rainfall (df5) and long-term rainfall (df95) were the best predictors for changes in ET due to prescribed burning activities (Table 1). Based on the GAMs developed in this study, soil (C:N) and terrain variables (slope, aspect, elevation) were not important factors for detecting change in ET.

State	Fire	Solar radiation (MJ m2)	EVI	df5 (mm)	df95 (mm)	T_{max} (°C)	T_{min} (°C)
ACT/NSW	[orange]	[orange]	[grey]	[grey]	[orange]	[orange]	[orange]
Victoria	[orange]	[orange]	[orange]	[grey]	[orange]	[grey]	[orange]
Combined	[orange]	[orange]	[orange]	[orange]	[orange]	[orange]	[orange]

TABLE 1. EFFECTIVE PREDICTORS (ORANGE SHADING) OF GENERALISED ADDITIVE MODELS DEVELOPED FOR PREDICTING EVAPOTRANSPIRATION. FIRE = PRESCRIBED FIRE, EVI = ENHANCED VEGETATION INDEX, DF5 AND DF95 = DISCOUNT FACTOR VALUE AT 5 AND 95% CONFIDENCE INTERVALS, T_{MAX} = MAXIMUM TEMPERATURE, T_{MIN} MINIMUM TEMPERATURE.

The validity of the of the assumptions of the GAMs and the adequacy of the model fit were evaluated using graphical techniques. The models were found to be suitable for describing ET due to the closeness of data points to the 1:1 line. The residuals were randomly distributed with no obvious patterns meaning that variance in the models were consistent across all estimations of ET (i.e. no systematic variation was present in low or high prediction values).

A better understanding of the effects of prescribed fire on hydrology and vegetation will help future forest management decision making and improve hydrology and vegetation modelling.

SOIL CARBON FINGERPRINTING

Milestone 2.3.4 Final report on advances in soil carbon fingerprinting – Quantifying the conversion of vegetation to ash for soil carbon fingerprinting (April 2020, Parnell D, Bell T, Possell M)

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. Much 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 provides 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 a well-documented association between fire severity and C and nutrient loss.

To begin research in this area, the first milestone (Milestone 2.1.4, delivered in March 2019) gathered together information from the literature and data we have amassed to better inform our planned laboratory studies. 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). A standard heating/combustion time of 60 minutes was adopted as this timing had been used repeatedly in the literature.

From initial laboratory trials it was evident that with longer heating time more biomass (dry weight) was lost. The greatest weight loss occurred when samples were heated at temperatures between 400 and 600 °C, regardless of the fuel type that was burnt. All material followed similar patterns with minimal weight loss (<10%) at 100 and 200 °C and maximum weight loss (90-100%) at higher temperature ranges of 400 to 600 °C. Bark however had variable weight losses at 300 °C, ranging from 55-95%. Losses of C and N also varied considerably with temperature. There was increased availability of N (albeit in very low amount, <5%N) when heated to 400 °C which may be related to the thermal decomposition of cellulose, hemicellulose and lignin. In comparison, C in surface fuels began to decrease when heated above 300 °C.

To further this investigation, a time series trial was done. For all fuel types, the greatest loss in biomass was recorded when samples were heated or combusted for 60 minutes. For heating or combustion of 30 minutes or less, C content was relatively consistent (49-58%). Temperatures above 300 °C and combustion periods of 30 minutes or greater was enough to lower the overall C content to 20-30%. The greatest loss of C was found when samples were combusted for a longer period, but residual C content varied for each fuel time (i.e. final C was 10% for bark, 14% for leaves and 29% for twigs).

With longer burn times and hotter temperatures, N content in surface fuels was also reduced. However, heating samples at 400 °C for 30 minutes or more showed a slight increase in N content for both leaf and bark material. This increase was not found with heating or combustion at lower temperatures (100, 200 and 300 °C) or for shorter periods (5 and 15 minutes).

As expected, the greatest changes in both C and N of surface fuels occurred at higher temperatures and longer burn durations, indicating that both fire intensity and residence time is important in understanding losses of C and nutrients during fire, particularly during low intensity prescribed burning. Better knowledge of C and nutrient losses during prescribed burning will lead to more precise modelling of C and N cycles in forest and woodland ecosystems.

ESTIMATING CARBON CONTENT OF SURFACE FUELS

Milestone 3.1.3 Final report of fuel conditions/vegetation model – Estimating carbon stocks and biomass in surface fuel layers (U2.3.10) (June 2020, Parnell D, Possell M, Bell T)

Over the last two years, models for estimation of biomass and C content 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 (Possell et al., 2019), and has been consolidated into this final report (Milestone 3.1.3). We intend to publish this research in due course.

The three litter fractions used in these models were: (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 content 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 has given us the ability to predict the nature of individual litter fractions. Using models developed from data collected from unburnt and burnt sites, we can estimate surface fuel biomass and the C load it represents. After further refinement and validation of these models as described in this report, the prediction range for surface fuel biomass is from 10.0-15.5 t DM ha -1 for unburnt sites and from 0-7.5 t DM ha-1 for burnt sites. For estimates of C in surface fuels, the prediction range is 5.5-7.8 t C ha-1 for unburnt sites and 0-3.7 t C ha-1 for burnt sites.

The goal for the final product coming from this research was to provide an easy-to-use tool that allows land managers to estimate C content in surface fuels before and after a prescribed fire. The information needed can be collected from the field when routine measurements of fuel loads are done during pre- and post-fire site assessments. 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 (Figure 2). 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 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 6.5 t DM ha-1 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.

The surface fuel models were validated by creating 'test' and 'training' data sets. The test data set was used to compare how close the model predictions were to the actual data, or training data set. There were reasonably strong relationships between the model predictions and test data. Samples collected from two low production forests (Stringybark Woodland and Grassy Box Woodland) and a high production forest (Blue Gum Forest) were used to represent surface fuel loads that were not typical of what we had already sampled. A weaker correlation between the model predictions and this independent site data was evident with larger mean absolute errors in the models. The biomass model had only small underpredictions but for C there were still significant under- and overpredictions.

This suggests that predictions of biomass and C in surface fuels for different forest types may not be accurate using our current models. Nonetheless, the ability to model the C content of individual fractions in surface fuel layers is important and assists in increasing accuracies in estimating C loss due to combustion of biomass.

We plan to further develop and test the fine fuel models to increase our confidence in them being more strongly representative of surface fuels from burnt and unburnt dry sclerophyll forests across south eastern Australia.

MODELLING CARBON EMISSIONS USING FULLCAM

Milestone 3.2.2 Model predictions for FRB – Model-data analysis of prescribed burning at sites in the Blue Mountains (January 2020, Pepper D, Bell T, Possell M, Parnell D)

With current climate scenarios of heat waves during extended dry periods, fire ignitions are inevitable. Current forecasts predict that Australia will experience an increase in frequency, intensity, duration and extent of heatwaves; longer fire seasons with more extreme fire danger days, longer days in drought and hotter days during drought (Jones and Bettio, 2019). With this, there is an increase in the need for prescribed burning and, so too, the need to understand more about them as prescribed burns often depends on prevailing conditions and the interaction with different ecosystems and attributes (vegetation type, fuel load and type).

As described in a previous milestone (Milestone 2.2.3; Karunaratne et al., 2019), the FullCAM model is a useful method for accounting for stocks and flows of biomass and C during prescribed fire events. This report described how empirical data collected from sites in the Blue Mountains region, was used to further test this model. This exercise required close collaboration with fire planners from the Blue Mountains Branch of NSW National Parks and Wildlife Service to determine their priority burn sites and to gain access to the sites themselves and relevant information about location, vegetation type and fire history. Sites were chosen to complement sites sampled previously and to match the vegetation type that we have concentrated on. These sites were sampled in May-September 2019 according to our sampling strategy (Gharun et al., 2015) and subsequent analysis determined how closely the predictions match with actual biomass and C losses after prescribed burning (see Milestone 3.3.1).

It was evident from field observations that understorey biomass, understorey leaf area index (LAI) and surface litter are directly affected by prescribed burning. Simulated effects of prescribed burns on C stocks were sensitive and quantitatively balanced as the reduction of C stocks tallied with C emitted (Figure 3).

FullCAM is currently a useful framework for tracking the changes in C stocks that are due to low intensity fire events such as prescribed burns. Further alignment between field data collections, model inputs and outputs for a range of sites are likely to promote a greater understanding of the effect of prescribed burning on

C cycling, post fire recovery and regrowth, and has the potential to also understand the changes in nutrient cycling after fire.

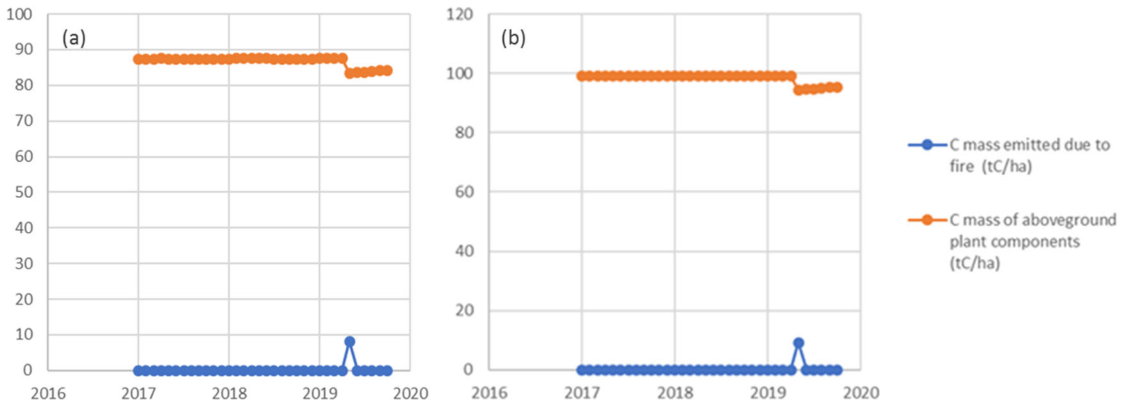

FIGURE 3. SIMULATED OUTPUTS FOR CARBON (C) EMISSIONS FROM PRESCRIBED FIRE AND THE IMPACT ON ABOVEGROUND PLANT COMPONENTS FOR TWO SITES SAMPLED IN THE BLUE MOUNTAINS: (A) BELMORE CORSSING AND (B) ROCKY WATERHOLES. NOTE DIFFERENT MAXIMA FOR Y-AXES INDICATING GREATER ABOVEGROUND BIOMASS AT BELMORE CORSSING YET SIMILAR PREDICTED EMISSIONS DUE TO PRESCRIBED BURNING.

Milestone 3.3.1 Model predictions for FRB – Model predictions for fuel reduction burning of eucalypt open forest in the Greater Blue Mountains region (CM 3.2.11) (May 2020, Pepper D, Bell T, Possell M, Parnell D)

In this study, we examine the suitability of the FullCAM framework for simulating the effect of prescribed burning on eucalypt open forest (as defined in FullCAM) at four sites in the greater Blue Mountains region that underwent prescribed burns in April-May 2019. We made use of empirical data collected from field sites during the last 12 months to derive and estimate forest components, some of which are suitable for comparing to simulated values. Other objectives were to explore the alignment of the FullCAM framework with these field data collections and test the suitability of FullCAM for simulating the effect of prescribed burning on this vegetation type.

The diameter at breast height of overstorey and understorey trees, leaf area index (LAI) and surface litter fractions were important measurements for estimating production, allocation, turnover (litter input to surface debris) and breakdown (output from surface debris) of C pools of forest components and hence, for calibrating FullCAM. Measurements for paired burnt/unburnt plots were key to estimating loss of C from forest component pools to the atmosphere due to prescribed fire. Simulation of unburnt forest component pools were reasonable as a calibration, although improvements in simulating fractions of surface litter would probably improve simulations of the effect of prescribed fire on forest component pools.

Some of the key assumptions for this modelling were as follows:

1. The understorey biomass and CWD are affected by prescribed burning to a similar degree to that of surface litter. Qualitative observations revealed that much of the live understorey leaf fraction was burnt, which was supported by estimates of understorey LAI. Likewise, much of the understorey live twig fraction was burnt, bark on understorey live saplings and woody shrubs was blackened or charred, and some of the smaller trees were killed.

2. Three estimates for the twig fraction of branches were used, all of which were site-specific.
3. Estimates of the understorey fraction of total aboveground biomass were either related to the inverse of tree height, the inverse of LAI and tree height or set as 1-10% of aboveground biomass.
4. Estimates of leaf litterfall used LAI, a constant value for specific leaf area (SLA), and leaf mass as a proportion of aboveground biomass. Similarly, bark litterfall was estimated as a proportion of aboveground biomass and twig and deadwood litterfall were estimated as a proportion of branch biomass.
5. Turnover of fine and coarse roots were a set proportion each of these belowground fractions.
6. Surface fuel from two sites were used to guide litter turnover and breakdown rates.

From this 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 C accounting framework of FullCAM. While the generic framework of FullCAM is suitable for modelling C stocks and flows in eucalypt open forest systems, improvements to more closely simulate the effect of prescribed burning on C stocks and flows are required.

SOIL CARBON AND FIRE SEVERITY

Milestone 3.3.2 Final report/ms on soil carbon and fire severity – Near infrared spectroscopy as a new fire severity metric (April 2020, Parnell D, Bell T, Possell M)

Fire can cause changes in C and nutrient pools through heating (volatilisation) and combustion of biomass. Ash and char production 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 (Bento-Goncalves et al., 2012). In this technical report we describe how visible-to-near infrared (vis-NIR) spectroscopy data can be used to inform combustion condition of surface fuels. We show how the use of vis-NIR spectroscopy can reduce inaccuracies associated with subjective colour matching and poor colour correlation when using automated colour conversion programs. This study indicates that there is great potential for vis-NIR spectroscopic technology to be used to determine fire severity according to the colour of residue after fire. Background information and baseline data for this investigation were presented in Milestone 2.3.4 (see above) and Milestone 3.1.4 (submitted in January 2020).

Samples of leaves, twigs and bark representing typical surface fuels from forests 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 vis-NIR spectroscopy.

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 (see example in Figure 3). 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 vis-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 vis-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 vis-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.

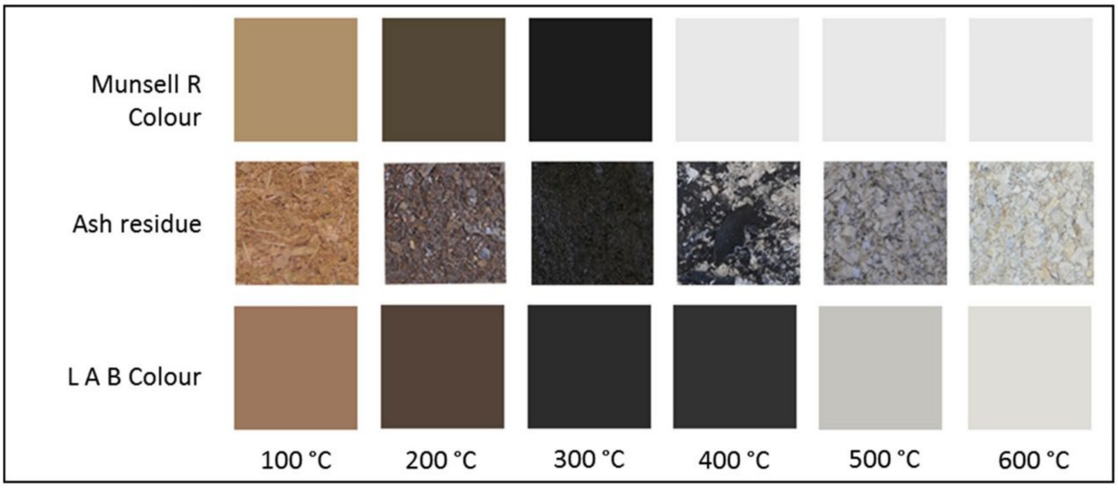

FIGURE 3. AN EXAMPLE OF THE COMPOSITION OF MUNSELL COLOURS, RESIDUES AND L*A*B COLOUR OF LEAVES HEATED AND COMBUSTED AT TEMPERATURES BETWEEN 100 AND 600°C.

Although Munsell colour matching has been used in soil science for decades, advancements in modern technology have permitted greater precision in the measurement of colours, eliminating the need for subjective visual assessment and removing the limitation in the range of colour tones available. As an alternative, the CIE L*a*b* system has been developed (Kirillova et al., 2015). The system is physically-based, mathematically-oriented and can be more reliable than colour charts due to the closeness it has to human vision (Marques-Mateu et al., 2018). From the study presented here, we support the use of the L*a*b* colour system to characterise char and ash residues from combustion of surface fuels. On the basis of the results presented in this report, we will continue this research by testing the use of portable vis-NIR scanning to determine fire severity in the field.

The vis-NIR spectral data was also used to develop predictions of C and N content of combustion residues, as well as the temperature that it was formed at. This was done using a partial least squares (PLS) regression model. The data was analysed together as a large grouping in the PLS regression model instead of being analysed individually in their logical groupings (e.g. fuel type, heating or combustion temperature and respective %C and %N values). This approach was taken to emulate a ‘real world’ prediction as contributing components are likely to be mixed and, as such, a prediction that incorporates a combined analysis of all materials would hypothetically provide a more accurate prediction.

Partial least squares regression models related to temperatures at which residues were produced resulted in relatively strong predictions (i.e. R2 values of up to 0.90) but weaker predictive power for C (%C) and N (%) content in surface fuels. Regardless of this, it is feasible to predict C and N in ash residues and the temperature at which fuels were combusted with vis-NIR spectroscopy.

UTILISATION AND IMPACT

OUTREACH

During the past 12 months we have continued to provide bi-monthly newsletters to end-users and researchers as a means to inform them of our research. This exercise generated different levels of interest depending on the topic:

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

EXPERT OPINION

Other evidence of our research impact during the year included:

- Tina Bell as an invited speaker at the Prescribed Burning – Evidence and Policy conference in Perth in August 2019. She presented a paper titled: 'Prescribed burning for multiple objectives – the case for carbon sequestration'. She was also an invited speaker at a one-day symposium titled 'Putting lessons into practice: reflecting on water management in the face of fire' held at ANU in early March. Her presentation was titled: 'Competing for resources after fire – trees need water too'.
- Tina Bell participated in 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 about prescribed burning. Her presentation was titled: 'Prescribed burning for multiple objectives'. The event had more than 500 attendees.
- 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.

RESEARCH COLLABORATIONS

On-going collaborations that were maintained during the past 12 months or established include the following:

- National collaboration by David Pepper with researchers from CSIRO towards better incorporation of prescribed burning into FullCAM.
- Collaboration with international researchers at: (i) the **Polytechnic of Torino** for the European call LC-CLA-15-2020: Forest Fires risk reduction: towards an integrated fire management approach in the E.U. in the Horizon 2020 programme; (ii) **University of Padova** and University of Torino, Italy with a poster presentation at the European Geosciences Union General Assembly in May 2020. The poster was titled: 'New methodology for mapping wildfire risk in the wildland-urban interface'; and (iii) **University of California**, Davis-University of Sydney collaborative fire response initiative with Tina Bell as the Lead Academic.

IMPACT OF PUBLICATIONS

The Impact Factor of the journals we have published in during the project and the number of times each article has been cited or viewed is provided in Table 2. For detail of each publication see Publications List below.

Peer reviewed article	Times cited	Journal	Impact factor
Possell *et al.* (2015)	10	*Biogeosciences*	3.951
Jenkins *et al.* (2016)	12	*Forest Ecology and Management*	3.126
Wang *et al.* (2016)	7	*Energy and Fuels*	3.021
Gharun *et al.* (2017a)	4	*Journal of Environmental Management*	4.865
Gharun *et al.* (2017b)	1	*Forest Ecology and Management*	3.126
Wang *et al.* (2017)	3	*Energy and Fuels*	3.021
Gharun *et al.* (2018)	2	*Science of the Total Environment*	5.589
Wang *et al.* (2019)	0	*Frontiers in Mechanical Engineering*	1.390
Yu *et al.* (2019)	0	*Water*	2.524
Gormley *et al.* (2020)	325 views	*Fire*	N/A

TABLE 3. SCIENTIFIC IMPACT OF PEER-REVIEWED PUBLICATIONS FROM THE PROJECT. THE JOURNAL FIRE IS A NEW JOURNAL AND DOES NOT YET HAVE AN IMPACT FACTOR ASSIGNED (N/A).

UNDERGRADUATE STUDENT RESEARCH

As part of our academic impact, we have hosted or advised a number of postgraduate and undergraduate students over the past 12 months. Student projects 1 and 2 were completed in August 2019 and Student projects 3 and 4 were completed in November 2019. Student projects 5-7 commenced in February 2020 and will be completed in November 2020.

Student Project 1: Matthias Geising – Ashes to ashes: the nature of ash produced from wildfires

This research involved laboratory-based combustion studies and measurement of the change in biomass, C and N content of three types of surface fuel (bark, leaves and fine fuel) over time (5, 15, 30 and 60 minutes heating) and with temperature (25, 100, 200, 300, 400 and 500°C) to determine how long these fuel types need for complete combustion. This project complemented work done in Project 4 and provided information relevant to Milestone 2.3.4.

Student Project 2: Marisa Estefania González Pérez – Flammability of dry sclerophyll forest litter

The aim of this project was to test the accuracy of recently developed empirical models for predicting flammability metrics of leaf litter collected from dry sclerophyll forest (Gormley et al., 2020). Surface fuels from sites sampled in the Blue Mountains (see Milestone 2.4.2) were used.

Student Project 3: Zhihan Michelle Wang – Ashes to ashes: the nature of ash produced from wildfires

This study measured the amount of biomass, C and N lost through volatilization and combustion with controlled heating and burning of plant biomass (leaves, twigs, bark, decomposing material) and surface soil (0-10 cm) collected from sites sampled in the Blue Mountains (see Milestone 2.4.2). All fuel types were heated and combusted at six different temperatures (100, 200, 300, 400, 500, 600°C) for 60 minutes. A colour chart was developed as an indicator of colour change of fuels with temperature and results generated were used to complement data presented in Milestone 2.3.4 and to inform Milestone 3.3.2.

Student Project 4: Marc Manzoni – Germination potential of native plant species

This project investigated 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 as an agricultural enterprise as part of the developing native food industry. Treatments simulating the effect of fire were used: smoke and ash, and dry heat, and wet heat (boiling water). Responsiveness to germination treatments varied greatly between species.

Student Project 5: Haruto Ima – "Ashtablishing" guidelines for interpreting NIRS data from burnt plant residues

This study aims to further calibrate and test models for combustion residues of surface fuels using NIR spectroscopy. Residues remaining after burning leaves, twigs, bark, fine fuel and surface soil in previous studies will be scanned with NIR spectroscopy and data will be analysed and added to existing predictive models (see Milestone 3.3.2). Ash residues collected from prescribed burns will be used to test the accuracy of models developed.

Student Project 6: Joshua Loughlin – Regreening the land: investigating the response of native grasses to simulated disturbances

The aim of this project is to evaluate the recovery response to disturbance (cutting and fire) of five native grass species that have undergone prolonged water stress (i.e. an extended annual drought period). To do this, disturbance treatments which simulate (i) grazing and harvesting will be applied in the field and (ii) grazing and prescribed burning will be applied under controlled conditions (pot culture). The regrowth capacity (biomass accumulation and C content) will be quantified and, along with auxiliary information (e.g. flammability traits; photosynthetic capacity and productivity; chemical composition), will be used to compare the response capacity of C3 and C4 grasses.

Student Project 7: Tallulah Dods – Fire and rain: flammability of subtropical rainforests and wet sclerophyll forest

This project will investigate the relationship between leaf traits and flammability of lowland subtropical rainforest and wet sclerophyll forest vegetation. A species list from sites in the Nightcap National Park, NSW has been compiled to direct efforts for sourcing some of the most from the Sydney basin area. Samples will be used to measure leaf traits and, where possible, flammability traits using a variety of laboratory techniques. This study will contribute to understanding fire behaviour in rainforests and managing the risk to human and ecological assets as the likelihood of bushfires increases in these areas.

NEXT STEPS

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. The final milestone (Milestone 3.4.1 Synthesis Report summarising all project activities) will be delivered in September 2020. Future research and reporting activities will include the following:

- 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 related to C transformation during fire: (a) using near infra-red spectroscopy of combustion residues to determine fire intensity, (b) detection of changes in soil C after fire from satellite imagery, and (c) interrogation fire severity maps with patterns of heterogeneity of surface fuel combustion. Part (a) is already being done as part of Honour student research projects in 2020.
- Continue fuel flammability research incorporating different vegetation types and metrics for leaf form and chemistry and plant and fuel structure. This is already being done as part of Honour student research projects in 2020.
- Convert Milestone reports and student research into peer-reviewed publications (see below).

PUBLICATIONS LIST FOR LAST 12 MONTHS

PEER-REVIEWED JOURNAL ARTICLES AND BOOK CHAPTERS

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.

Gormley AG, Bell TL, Possell M (2020) Non-additive effects of forest litter on flammability. *Fire* 3, 12; doi:10.3390/fire3020012

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

TECHNICAL REPORTS AND POSTERS

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.

Bell T, Possell M, Pepper D, Parnell D, Karunaratne S, Yu M, Gharun M, Neumann M, Adams M (2020) 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.

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.

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.

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.

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.

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.

Taccaliti F, Marzano R, Rizzolo R, Fischetti D, Bell T, Lingua E (2020) New methodology for mapping wildfire risk in the wildland-human interface. EGU 2020 Poster presentation.

Yu M, Pepper D, Bell T, Possell M (2020) Calibration of water and carbon model using field/existing data. Milestone 2.3.3 Technical Report, Bushfire and Natural Hazards CRC, 24 p.

TEAM MEMBERS

The research team operates from two bases, one in New South Wales (University of Sydney) and one in Victoria (Swinburne University).

RESEARCHERS AND SUPPORT STAFF

University of Sydney

Assoc. Prof. Tina Bell (Project Leader)

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Dr Senani Karunaratne (Postdoctoral Fellow)

Dr Mengran Yu (Postdoctoral Fellow, Landscape Modelling)

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Mr Haruto Ima, Honours candidate, University of Sydney

Mr Joshua Loughlin, Honours candidate, University of Sydney

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Jacqueline Frizenschaf, SA Water

Melissa O'Halloran, NSW Rural Fire Service

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