bushfire CRC

FIRE IN THE LANDSCAPE

FINAL PROJECT REPORT

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Executive summary

The four research projects in the 'Fire in the Landscape' program were positioned within the 'Managing the Threat' research stream of the Bushfire Cooperative Research Centre (CRC). Over the past four years (2010-2014), researchers from the University of Melbourne and the University of Sydney have investigated the effects of fire on water quality and quantity and the changing nature of above and below ground carbon stores after fire. Two of the research projects were developed in response to a key challenge currently facing land managers – maintaining water quality and quantity from forested catchments. Another two research projects were developed to cope with an important issue emerging from climate change and increasing greenhouse gases in our atmosphere – quantifying carbon losses during fire. The projects described in this final report have delivered some innovative research focused on these two broad areas.

The 'water-based' research projects were:

- *Fires and hydrology of south-eastern Australian mixed-species forests* (Project 1)
- *Quantifying risk of water quality impacts from burned areas* (Project 2)

The 'carbon-based' research projects were:

- *Environmental impacts of prescribed and wildfire – emissions management* (Project 3)
- *Greenhouse gas emission from fire and their environmental effects* (Project 4)

The Bushfire CRC research projects were conceived to take best advantage of the capabilities and expertise of researchers from the University of Melbourne and the University of Sydney and the facilities available at each institute. Both the carbon- and water-based projects were developed to tackle research questions that, at a high level, were similar but were approached from quite different angles. Regardless of this, the focus of the research was always intended to be practical and appropriate for End User requirements.

Projects were designed to be complementary with the view to make them as integrated as possible as the research topics developed and matured. Assimilation of the four projects was achieved in a number of ways including the use of compatible field sites in Victoria, employing well-matched approaches to research and having regular whole-group meetings. Arguably the most effective means of consolidation was consistent presentation our research as a complete 'Fire in the Landscape' package at Bushfire CRC workshops, research forums and in written format. The final report presented here is the culmination of our combined efforts to develop and deliver excellent science with a strong End User focus.

The Bushfire CRC research presented has been achieved through a wide range of field- and laboratory-based studies. Researchers have worked closely with End Users to address their needs in gaining a greater understanding of what happens to critical components of the environment when there is planned and unplanned fire in the landscape. The research team has produced high quality research that End Users can have confidence in and can trust. For the wider scientific community, the research has been published in a number of peer-reviewed journal articles and presented at national and international conferences. For the End Users audience, our research has been described in a wide array of formats including Bushfire CRC Fire Notes, magazine articles (e.g. Fire Australia, Summer 2014-2014), local conference presentations and research forums using plain language and concentrating on information relevant to fire and land managers. More importantly, ongoing interaction with End User agencies has been achieved through regular meetings and laboratory and field visits.

The four 'Fire in the Landscape' projects are described in considerable detail in the following pages of this report. Here, however, brief descriptions of the projects and how they have added to our current knowledge are presented here.

Water quality and quantity
The two water-based projects were concerned with the role of planned and unplanned fire in determining water quality and quantity from catchment forests in south-eastern Australia. The broad management questions that were considered by these two projects were how much water is used by trees after fire, how much water goes into catchments, and is the quality of this water fit for use in towns and cities? One of the water-based projects focused on determining the hydrology of mixed-species forests by collecting empirical data and modelling the water balance in regenerating *Eucalyptus* forests following bushfire. The second project quantified and modelled the risks to the water supply of catchments burnt by bushfire and used this information to predict the reduction to these risks if planned fire is introduced into catchments.

In southern eucalypt forests, water-use by vegetation is directly dependent on water availability. Patterns and amounts of rainfall can be assessed at reasonable spatial scales but prior to the research presented here, we did not have a complete understanding of how much water trees need or how tree water-use varies across the landscape and in time. According to estimates available at the start of Project 1 (*Fires and hydrology of south-eastern Australian mixed-species forests*), tree water-use may be as much as 20% in some forests (Langford 1976; Kuczera 1987; Vertessy *et al*. 2001). However, past research has focused on tree water-use of eucalypt forests that are killed by crown-removing fire and regenerate *en-masse* from seed. Little was known about tree water-use of resprouting eucalypts which constitute extensive mixed-species forests in Victoria and New South Wales, particularly at lower altitudes. Such forests are likely to have different patterns of water requirements compared to forests that regenerate from seed.

It is important that estimates of tree water-use are refined as the water used by vegetation dictates water yield or run-off from forested catchment areas (Mitchell *et al*. 2012). Previous models of tree water-use were based on an empirical soil-plant-atmosphere (SPA) model described and used by Williams *et al.* (1996, 2001) and Zeppel *et al.* (2008). This model did not take into account process-based variables such water loss at the leaf-level nor did it allow incorporation of landscape-scale variables such as climate and topography. To address these shortcomings, Project 1 aimed to quantify and model overstorey tree water-use in mixed-species forests regenerating after bushfire.

It was found that after the crown-removing fires in 2009, the water-use of burnt trees was similar to nearby unburnt trees (see Gharun *et al*. 2013b). Within the four-year timeframe of Project 1, the regenerating canopy developed from many small branches distributed evenly along the stem to fewer and larger branches which will eventually form a full canopy (Turnbull *et al*. 2014, in review). It was found that as the leaf form and canopy structure slowly changed after fire, tree water-use did not change. The data collected from field sites were used to calibrate a process-based model developed as part of the project (see Buckley *et al*. 2012). This new model of tree water-use is based on the resistance to water loss imposed by leaves (see Gharun *et al*. 2013a). As a result of rigorous and intensive campaign-style sampling, the model is now being tested in conjunction with whole-of-catchment models for prediction of tree water-use after fire.

Erosion events following recent wildfires in south-eastern Australia have shown that burnt areas represent a real risk to water quality in water supply catchments. For example, following the 2003 fires, Bendora Reservoir (the water supply for Canberra) experienced turbidity values 30 times the previously recorded maximum, forcing water restrictions to be put in place. In the US, post-fire debris flows have recently been identified as a key erosion process leading to water quality impacts (Robichaud *et al*. 2007; Cannon *et al*. 2010). In addition, models have been developed to combine the frequency and intensity of fire with rainfall across a landscape in space and time (Benda and Dunne 1997; Istanbulluoglu *et al.* 2004). Prior to the research described in Project 2 (*Quantifying risk of water quality impacts from burned areas*), the magnitude of the risk to water quality as a result of debris flows and the degree to which this risk is modified by management actions was unknown (Cawson *et al*. 2012).

As a result of Project 2, an understanding of the relationships among fire severity, peak flows and sediment transport from headwaters has been developed (Jones *et al*. 2011; Lane *et al*. 2011; Nyman *et al*. 2011b). Slope and vegetation are important predictors of the occurrence of debris flow but there are many interactive processes occurring (Nyman *et al*. 2013; Nyman *et al*. 2014, *in review*). A model representing water quality risk as a function of rainfall and fire regimes within a particular catchment has been developed and tested to extrapolate process-based (site-specific) responses to landscape-scale catchments (Nyman *et al*. 2013). This model has been tested under scenarios of climate change (Jones *et al*. 2014, *in review*; Nyman *et al*. 2014, *in review*) and will be tested further in other catchments to determine how universal the patterns are.

Carbon balances and fire

Fire directly impacts the carbon balance of forests through emissions of carbon dioxide, volatile organic compounds and other greenhouse gases formed during combustion of vegetation and litter. Plant biomass is also converted to various forms of carbon-containing ash and charcoal that may stay on-site and be incorporated into the soil profile or removed from the site. The two carbon-based projects in the 'Fire in the Landscape' program investigated the fate of carbon after fire using complementary laboratory- and field-based studies. At the beginning of both projects there was only a rudimentary knowledge of the direct effects of planned fires on carbon balances in forests. Comparable information was available for savannas and grasslands in northern Australia but as it was derived from data collected from considerably different types of vegetation, it could not be applied with any great confidence to southern forests. Consequently, there was very little empirical data available to model carbon losses during fire. The most recent estimate of the amount of carbon emitted to the atmosphere from fires in Australia is 127 Tg C yr^{-1} (Haverd *et al*. 2013), but this value is primarily based on data relevant to northern Australia and extremely limited data from southern Australia.

At the start of the Project 3 (*Environmental impacts of prescribed and wildfire – emissions management*) there had been some efforts to quantify carbon pools in *Eucalyptus* forests of south-eastern Australia (e.g. Simkin and Baker 2008; Lindenmayer 2009; Benyon and Lane 2013). However, the forest types studied were not subject to regular prescribed burning so were of limited value to land managers for estimation of carbon stocks. As suggested above, there were also a number of studies investigating changes in carbon pools and emissions during fire in northern Australia but the vegetation types investigated were typically grassland or savanna (Hurst *et al*. 1994a; b; Russell-Smith *et al*. 2009; Paton-Walsh *et al*. 2010). As a result, the potential impacts of fire on carbon pools in open eucalypt forests that are burnt regularly were unknown.

The challenge in Project 3 was to adequately measure changes in both small and large carbon pools in forests across the south-eastern landscape to model carbon emissions to the atmosphere during burning. Eleven field sites were established in dry sclerophyll forests across Australia in Victoria, South Australia, the Australian Capital Territory, Tasmania and Queensland and were systematically sampled before and after prescribed burning or opportunistically after bushfire. Sampling protocols were trialled extensively to ensure that they were suitable for detecting small differences in carbon pools after fire (Volkova and Weston 2013a). In particular, sampling of carbon held on the forest floor and in the upper soil layer required special attention to properly measure carbon losses and redistribution as ash and charcoal.

In forests in southern and eastern Australia, the greatest proportion of carbon is held aboveground in tree biomass but the total amount is dependent on site location (Volkova and Weston 2013a). The most dynamic carbon pools – showing the greatest losses of carbon on a mass-loss basis – are in litter, understorey vegetation and coarse woody debris. An important and practical discovery from this project was that carbon pools represented by coarse woody debris represent a significant amount of carbon but are not properly accounted for in emissions estimates (Volkova and Weston 2013a; b).

As a result of Project 3, our knowledge of forest carbon balances has improved drastically by quantifying the impact of fire on forest carbon stocks (Volkova and Weston 2014) and providing more reliable estimates of the magnitude of emissions produced during planned and unplanned fire (Volkova *et al*. 2014). It was found that planned fire release only a minor fraction of the carbon stored in forests (2-3%) and that emissions from planned burns and bushfire in fuel-treated forests was half that compared to emissions during wildfire in long unburnt forests. It was also established that 2% of the carbon that was previously considered to have been lost to the atmosphere in gaseous and particulate form remains in the forest through redistribution to the forest floor (Volkova and Weston 2014, *in review*). Earlier estimates of carbon losses during burning were not necessarily inaccurate but as a result of this study, the transformation of carbon into different forms has been better described.

Reliable estimates of carbon emissions from planned and unplanned fire are required to assess the impact of smoke on the atmosphere. Gaseous emissions from fire can be estimated if variables including the area burnt, mass of fuel burnt, combustion completeness and emission factors for trace gases are known (Russell-Smith *et al*. 2009). Prior to the start of Project 4 (*Greenhouse gas emission from fire and their environmental effects*), smoke composition research had concentrated on emissions from fire in savanna in Australia (Hurst *et al*., 1994a; b; Paton-Walsh *et al*., 2010), with few studies available for temperate forests in south-east Australia (Hurst *et al*. 1996). As a consequence of research completed in this project our knowledge of greenhouse gas emissions from fires has vastly improved.

In contrast to the field-based project partnered with this one, laboratory-based experiments have revealed processes underlying the flammability of fuel. For example, the moisture content of fuel has an integral role in flammability (Possell and Bell 2013) and therefore in fire behaviour. The high specific heat capacity of water relative to other compounds means that water acts as a latent heat sink. With increasing moisture content more energy is required to drive water out of the fuel instead of being used to heat the material to initiate combustion reactions. Consequently, combustion efficiency is reduced and there is an increase in the concentration of incomplete combustion products such as particulate matter, carbon monoxide and volatile organic compounds (Possell and Bell 2013). These compounds have significant impacts on human health and can affect vegetation (see Bell *et al*. 2013).

From the research done in this project it is clear that emissions of CO_2 and CO are dependent on the condition of the fuel but not necessarily the type of fuel (Possell and Bell 2013; 2014, *in review*). Testing of several species of *Eucalyptus* showed limited differences in flammability attributes or carbon emissions among species allowing us to identify general relationships encompassing these variables and fuel moisture content (Possell and Bell 2012). However, greater differences in flammability attributes and carbon emissions were detected among tropical and savanna grasses giving us some boundaries to the level of generalisation that can be made (Possell and Bell 2014, *in review*).

The overall amount of carbon lost to the atmosphere from prescribed burns in *Eucalyptus* lowland forests was found to range from 5.5-38.0 T C ha^{-1} depending on the calculation method used (Possell *et al*. 2014, *in review*). Within a single forest type, total emissions from prescribed burning were highly variable and depended on fuel load and completeness of combustion. Estimates of carbon losses made from studies conducted in Project 3 (6.7 T C ha^{-1}) were towards the lower limit of estimates from Project 4 highlighting that differences in emission estimates may be due to the calculation method used. In Project 3, carbon emissions were calculated according to the Australian National Greenhouse Accounting System using universal default values (National Inventory Report 2011) which tend to overestimate of the amount of biomass consumed during combustion. Despite the apparent disparity in estimates of carbon loss, both projects found that underestimation of carbon emissions during planned burning is also due to non-accounting of coarse woody debris.

Opportunities and new discoveries

From a researcher perspective it was exciting to produce research that had such tangible impacts. It was gratifying to progress from a conceptual representation of fire as a disturbance in water catchment processes to building a field-based dataset of post-fire responses and landscape sensitivity to testing water quality predictions with planned burns. Developing and testing a model for tree water-use and expanding it to a landscape-scale has been a long-awaited study. It was immensely satisfying to be able to contribute to improvements in national carbon emission estimates from forest fires when our capacity was severely limited before the start of our investigations. Many research challenges still remain and as always, new discoveries lead to even more questions that need to be answered. Our various interactions with End Users were rewarding and were a constant valuable reminder to make our research accessible to a wider audience.

An unprecedented number of postgraduate students working with the research teams at the University of Sydney and the University of Melbourne have completed are nearing completion of their research. They have not only advanced our state of knowledge about fire in the landscape but have worked in conjunction with fire and land management agencies on projects that are relevant and current. In this sense, the Fire in the Landscape program has trained a strong cohort of future fire researchers or managers.

As the research undertaken in these four projects comes to an end, data will continue to be developed into peer-reviewed publications, Fire Notes and research reports as appropriate. Researchers and postgraduate students will continue to present their research findings at national and international conferences. The final End User Workshop for Fire in the Landscape projects held in July 2013 consolidated our research findings and on-going collaboration with a range of End Users. An informal survey conducted immediately before this workshop indicated that the End Users had a good basic knowledge of the research projects and there was strong identification of the research teams with particular projects. The post-workshop survey identified that there was strong support for the research presented in the Fire in the Landscape projects as End Users included descriptive phrases such as ‘new knowledge’, ‘improved estimates’ and ‘better predictions’. There was also a resounding call for the water- and carbon-based research to continue in the future.

Impact statement from Lead End Users

Neil Cooper and Adam Leavesley, ACT Parks and Conservation Service.

The Fire in the Landscape research program was developed to address some of the key issues that land management agencies face in fire-prone forests in south-eastern Australia. The research projects concentrated on water supply, carbon emissions and smoke. The results from the water-based projects suggests that in the absence of further information, well-managed low-intensity hazard reduction burning in mixed-species eucalypt forests is unlikely to greatly impact on water yield or quality. The carbon-based research showed that current methods for carbon accounting need to be revised and provide approaches for better estimation of carbon emission from forest fires in south-eastern Australia.

Fires and hydrology of south-eastern Australian mixed-species forests (Project 1)
Water-use of vegetation in mixed-species eucalypt forests did not increase markedly during the recovery phase following a high intensity bushfire. The mechanism for tree recovery in these forests was resprouting. It is therefore unlikely that water yields from mixed-species catchments will not be as strongly affected by fire as those from the Ash-type forests, a forest type where much of the previous research has been conducted.

This information can be used by catchment managers and water supply authorities to determine optimal strategies for simultaneously managing fire risk and ensuring continuity of water supply. A model designed for use by agencies that will greatly simplify the process of estimating tree water-use is being finalised. The results from this project are directly applicable to mixed-species catchments in south-eastern Australia. Outside of this area, catchment managers and water supply authorities may be able to adapt this research by validating tree water-use models for new vegetation types. There is the potential for this research to be used at a strategic level inform to water-related policy.

Quantifying risk of water quality impacts from burned areas (Project 2)
The reduction of vegetation caused by bushfires can lead to major soil erosion events. The likelihood of erosion increases with increasing fire severity, increased rainfall intensity and steeper slopes. It is also likely to be greater in areas of the landscape that are normally drier. In this research, a model that predicts the distribution of erosion events in space and time was developed.

The model is directly applicable to landscapes of the Great Dividing Range from Kilmore in Victoria to the boundary of the Sydney Basin. The model can be used by land mangers to identify areas susceptible to erosion to help locate sediment control measures and assist in planning of appropriate water supply and drainage infrastructure. End Users outside of the research area could benefit from the research by partnering with the researchers to fine tune the outputs for new areas. The work may also be useful at a strategic level to inform water-related policy. The key findings of the research are likely to be applicable worldwide, but specific predictions will vary depending on geology and soil type.

Environmental impacts of prescribed and wildfire – emissions management (Project 3)
The research done in this project found that in forests in south-eastern Australia, carbon emissions from planned burns were much lower than for unplanned burns. The calculation of emissions based solely on fine fuel load was found to significantly underestimate total carbon emissions mainly because of omission of the contribution of carbon from combustion of coarse woody debris in current carbon accounting methodologies.

The research can be used by land managers in south-eastern Australia to estimate their contribution to carbon emissions from planned burning in dry sclerophyll forests. The results may also provide a reasonable estimate of carbon emissions from burning similar forests found in other parts of Australia outside the study area.

Greenhouse gas emission from fire and their environmental effects (Project 4)
This project involved laboratory-based measurements of a range of carbon emissions from burning vegetation. It was found that 'wet' fuel produce less carbon dioxide and more methane than fuel with low moisture content. Emission factors were determined for various Australian fuels. In the case of eucalypts, emissions did not vary appreciably but flammability and carbon emissions for an introduced weed, African Love Grass, were higher than for other Australian grasses. It was noted that none of the gaseous components of bushfire smoke that were measured under controlled laboratory conditions were present in toxic quantities.

More accurate emission factors can be used by Australian and international jurisdictions to help manage greenhouse gases in the atmosphere. The identification of variable flammability within Australian fuels could potentially become an early warning indicator for fire managers, for example, in jurisdictions with introduced weeds. Recognition of potential differences in flammability between co-located fuels also introduces a new factor that may need to be accounted for in fire behaviour models. The differential emissions recorded from fuels with different moisture content could provide a mechanism for fire managers to manipulate emissions from planned burns in the future.

The new knowledge and understanding that has been developed from the 'Fire in the Landscape' projects has been transferred to agencies in a variety of ways. Field and laboratory site visits were particularly useful for delivering information to End Users and recognises that people take up information in different ways. The field demonstration of the water-based projects provided an important bridge for the gap between research and operational delivery. Researchers had a chance to demonstrate the scope of the research being doing and End Users could gain an appreciation of the hard work required to collect data. Fire Notes were commented on by agency staff prior to publication and were circulated widely after publication. Workshops, meetings and conference presentations have been invaluable methods for communication of results from each of the projects.

The Fire in the Landscape program has provided key research required for understanding the consequences of putting planned fire into managed ecosystems. This type of land management activity needs to be supported by good management decisions and sound scientific research. State government agencies are tasked with managing the land in the most economically, sustainably, socially appropriate and scientifically-defensible manner using public resources. One of the most effective ways to achieve this is to foster close collaborations with relevant research partners. If End User agencies can work alongside researchers by providing input describing the research they need, the outputs of the research are more likely to be practical and adopted in day-to-day management. This is what the public, the government, managers and researcher should expect. End Users ultimately trust research bodies to deliver good science but developing close associations will engender far greater confidence and maintain ongoing collaboration.

For additional information on these projects see:

Nyman P (2012) Erosion risk to water resources in fire and rainfall regimes. Bushfire CRC Fire Note 90.

Volkova L, Weston C (2012) Environmental impacts of prescribed and wildfire – emissions management. Bushfire CRC Fire Note 96.

Possell M, Bell TL (2013) Smoke composition and the flammability of forests and grasslands. Bushfire CRC Fire Note 110.

Turnbull TL (2012) Quantifying the impact of fire on tree water use. Bushfire CRC Fire Note 115.

Fire Australia Magazine (Summer 2014-2014) Fire in the landscape – lessons learned. Industry publication for the Australasian Fire and Emergency Service Authorities Council, 35-36.

Project 1: Fires and hydrology of south-eastern Australian mixed-species forests

Research institute: Faculty of Agriculture and Environment, University of Sydney
Researchers: Tarryn Turnbull, Tom Buckley

Project summary

In all southern eucalypt forests, water use by vegetation (understorey plus overstorey) is directly dependent on water availability that varies strongly both seasonally and annually. Availability of water to the understorey is clearly dependent on the balance between rainfall and the water demands of overstorey eucalypts. Rainfall can be assessed at a reasonable spatial scale using Bureau of Meteorology resources but we currently lack models to predict the availability of water to understorey vegetation. In addition, we do not know how tree and understorey water use varies across the landscape but it may be as much as 20% of total water use in some forests. When considered together, the water use by overstorey and understorey vegetation dictates water yield or run-off from forested sub-catchments. Water yield is strongly leveraged to water use by vegetation such that a 5% change in water use may result in a 20% reduction in streamflow.

We have been developing approaches that allow us to quantify overstorey tree water use in relation to soils and climate, and models that allow extrapolation to annual time scales and sub-catchment geographic scales. We now need to develop this ability further such that it can be used with forests regrowing after fire – both bushfire and prescribed fire. Key questions are related to how resprouting eucalypts differ from eucalypts that regenerate from seed (e.g. Ash-type eucalypts). In particular, we know almost nothing about the water use of resprouting eucalypts and how this is affected by leaf anatomy and phenology. As our study sites were selected from areas burnt in the 2009 bushfires and form part of an important forest catchment for the supply of water to Melbourne, this was timely and wholly appropriate research. This project will fill an important gap in knowledge for modelling of tree water use in catchments in fire-prone forest.

A priori state of knowledge

Mixed-species forests constitute a considerable percentage of the catchment estate in south-eastern Australia. Most research into water use by eucalypts in south-eastern Australia has concentrated on the tall open forests dominated by *Eucalyptus regnans.* These forests regenerate by seed after fire, whereas mixed-species forests predominately regenerate vegetatively. As the eucalypts that dominate mixed-species forests differ in life history to *E. regnans* we cannot assume that the severity or longevity of reductions in catchment yield following fire will be the same. Recent work (Mitchell *et al*. 2012) in mixed-species eucalypt forests has shown that transpiration by the overstorey accounts for the majority of the water-budget for a catchment and that it is closely coupled with soil and climate.

We have been developing approaches that allow quantification of overstorey water use in relation to soil and climate for use with models that allow extrapolation to annual time scales and geographic scales of sub-catchments. Previously our models were based on the empirical soil-plant-atmosphere (SPA) model described and used by Williams *et al.* (1996, 2001) and Zeppel *et al.* (2008). As well as refining this model for resprouting mixed-species forests in north-eastern Victoria (Gharun *et al*. 2013a) we have published a new process-based model for tree water use, based on resistance to water loss imposed by leaves (Buckley *et al*. 2012). As such we will use the data arising from this project to predict water used by resprouting mixed-species forests in north-eastern Victoria. Once the model has been calibrated for these forests, it can be used catchment mangers for incorporation into whole-of-catchment models.

Research results

Our broad aim was to examine the eco-hydrology of mixed-species eucalypt forests as they regenerate after crown-removing fires. The primary question we wanted to answer for the mixed-species forests burnt in the 2009 fires in south-eastern Australia was do mixed-species forests follow the same trend as Ash-type forests and have a lengthy period of reduced catchment yield following crown-removing fire, or do mixed-species forests have a shorter period of reduced catchment yield following crown-removing fire?

Our secondary aims were to extrapolate the findings from our particular study sites to other forested areas, and to do this requires an understanding of leaf physiological processes. Leaves are the site of greatest water loss from trees, so our investigations centred on determining the nature and extent of changes in the structure and physiology of leaves of regenerating eucalypts from mixed-species forests. We needed to investigate what leaf properties exerted the most control over tree water use in juvenile leaves on epicormic branches, and what variables regulated gas exchange and leaf hydraulics in juvenile leaves on epicormic branches. Once we had a good understanding of the patterns of ontogenetic development of leaves on epicormic branches, we wanted to see how well their resistance to water loss could be described by existing eco-hydrological models. Specifically our research questions were:

1. How uniform are our forests with respect to those of the rest of the world, that is, could patterns in overstorey transpiration be explained by an existing eco-hydrological model such as “Soil-Plant-Atmosphere” (SPA)?

2. Can we develop a model for tree water use that bridges the gap between empirical models that are computationally efficient and have few parameters and detailed process models with many parameters?

3. Can we develop a model that can be used by the general public that is robust and has very minimal parameters that are easy to collect?

We designed and planned our experiments in January of 2010 (Table 1). Two separate experiments were initiated for this project: one to quantify overstorey tree water use and one to enable us to better understand leaf physiology. To quantify overstorey tree water use, we decided upon paired burnt and unburnt plots for each of the dominant species within mixed-species forests at Stanley in north-eastern Victoria. We wanted two locations where the forest type differed topographically: high- and mid-elevation. Our intent was to measure sap-flow and environmental variables throughout 2011 and 2012 but some aspects of the work began earlier in 2010. For the experiment designed to further our understanding leaf physiology in epicormic trees we needed three regenerating trees of the two most dominant species. We wanted to measure changes to the physiology and structure of leaves as the trees regenerated, so decided upon annual campaigns for the duration of the project.

Table 1. Timeline of key activities.

Key activities	2010-2011	2011-2012	2012-2013	2013-2014
Site selection and establishment in north-east mixed-species forests (March)				
First targeted field campaign – establishment of measurement protocols (April)				
Collection and evaluation of base-line data				
Literature review				
Second targeted field campaign (April)				
Overstorey water use and model development and preparation of manuscript				
Data analysis from second targeted field campaign and preparation of related manuscript				
On-going collection of water use data and site maintenance; specific data collection for LAI (March, December)				
Third targeted field campaign (April)				
National/international conference presentation				
Data analysis from third targeted field campaign and preparation of related manuscript				
On-going collection of water use data and site maintenance; specific data collection for LAI (April)				
Decommissioning of site				
Final data analysis and preparation of related manuscript				

Experiment 1: Understanding leaf physiology

We established the field sites for studying leaf physiology in March 2010. As the developing canopy needed to be sampled on a regular basis, the site had to be able to accommodate the large equipment required (i.e. a customised fire truck with an elevated work platform). A suitable site was found with recently burnt trees adjacent to a secluded clearing. In April 2011, high- and mid-elevation sites were selected and established for studying tree water use.

To understand how leaf physiology changed with recovery from fire we had sampling campaigns in April 2010, 2011 and 2012. Each year we measured the structure of the canopy and leaf area, leaf type and patterns of distribution along the bole, aspects of leaf physiology such as leaf anatomy (i.e. venation patterns, hydraulic conductance of leaves, stomatal features), leaf chemistry (nitrogen and bulk carbon isotope signature), leaf gas exchange (stomatal conductance, photosynthesis and respiration), and leaf water status (water potential and Pressure-Volume curves).

The rate at which water flows from soil to the atmosphere through a plant is influenced by the demand for water by leaves in the canopy. We needed to know the 'leafiness' (leaf area index; LAI) of the regenerating forests, along with the structural properties of leaves to assess how much water was used by the canopy throughout the day and during different times of the year. In forests that regenerate via resprouting, photography sometimes does not work particularly well as leaves are clustered tightly around the trunk and stems and images are difficult to interpret. In situations like this, LAI photography was supplemented with actual measurements of leaf area. We counted the number of branches and measured their size along the tree trunk and stems, and determined the relationship between branch size and leaf area. From these measurements we calculated the total area of leaves for each tree.

We also investigated other sources of resistance to water loss within an individual leaf. The 'porosity' of leaves was determined by counting the number of stomata, measuring their size and how wide the stomata can open (the maximum aperture of the stomatal pore). Patterns in leaf anatomy were further examined to calculate leaf hydraulic conductivity. This involved measuring the perimeter of 'wet' cells (that is, types of cells known to evaporate water) in relation to the volume of airspace within a leaf, and coupling these measurements to other anatomical features of leaves such as the density of water-supplying veins and proximity of stomata.

Trees cannot photosynthesise without losing water through their stomata, so measuring and understanding the photosynthetic physiology of regenerating eucalypts is another aspect we studied. During the month of April in 2010, 2011 and 2012 we assessed aspects of leaf physiology and all measurements were made *in situ* using an elevated work platform. Using one leaf (the youngest fully-expanded specimen) selected at three heights for each of the study trees, we measured carboxylation capacity (V_m25), maximum potential electron transport rate (J_m25) and dark-adapted (>12 hr in darkness) leaf respiration (R_d) using two specifically calibrated infrared gas analysers (Li-Cor6400, Lincoln, NE, US). During each campaign, on the same trees and at the same measurement heights, we also measured stomatal conductance (g_s) and leaf water potential (Ψ) over the course of a day.

The data analyses for this experiment have been completed and manuscripts have been prepared for peer-review and formal presentation (see Buckley *et al*. 2012; Turnbull *et al*. 2014, *in review*). This experiment has been described in Fire Note 115 (August 2013) and results have been presented at Bushfire CRC workshops or Research Advisory Forums and as poster presentations at the annual Bushfire CRC conference in 2013.

Experiment 2: Overstorey tree water use

To quantify overstorey tree water use we continually measured water used by individual trees using the Heat Ratio Method. Sensors were installed into the sapwood of trees of a range of sizes to measure the rate of movement of water through the stem. Each probe set consists of two needles and a heater probe and each needle contains two thermocouples at different lengths (to accommodate varying sapwood areas). Sap velocity is determined via the ratio of the increase in sapwood temperature above and below a heater needle following a heat pulse. Sap velocity is proportional to heat pulse velocity. Sap-flow was recorded at half-hourly intervals. Sites were visited fortnightly for the duration of the experiment to upload data and to ensure equipment was functional (i.e. goat-proofing, fixing burnt-out probes, cleaning solar panels). Individual tree measurements of sap-flow were then scaled to overstorey tree water use.

The amount of water transpired depends on the total amount of sapwood in the forest. To calculate how much water is transpired by the whole forest, the number of trees in a given area needs to be known, along with what proportion of their trunk consists of sapwood. We characterised species-specific relationships between sapwood area and bole diameter and measured the radial and azimuthal variation in sap-flow for a subset of trees. Using these relationships and information from our initial site inventories, we were able to calculate an estimate of tree water use per hectare for the overstorey trees.

We also periodically visited the sites to capture images of the leaf area of overstorey trees and understorey vegetation. Overstorey leaf area was measured as the average of repeated (at least 25) upward looking digital images (Macfarlane *et al*. 2007). Overstorey and understorey foliage cover was also photographed using the methods of Macfarlane and Ogden (2011). From these images we estimated LAI of the understorey. These images were collected three times; March and December 2011 and again in April 2012.

Furthermore, we periodically measured parameters that describe the physiology and hydraulic features of leaves from burnt and unburnt trees. We measured these physiological variables on leaves of regrowth and mature trees using a hydraulic platform. Three trees of each species were measured twice during 2012 (early March and late April) for photosynthesis, stomatal conductance, leaf transpiration rate and leaf water potential.

We found that soils tended to be wetter under regrowth forests, as was the atmosphere within the canopy (Fig. 1; Gharun *et al*. 2013b). As trees regenerate from crown-removing fire, mixed-species eucalypt forests do not use more water than their unburnt counterparts (Fig. 2; Gharun *et al*. 2013b). This is in stark contrast to the water use of regenerating Ash-type forests and can be explained by: slower sap-flow in resprouting trees, a relatively small increase in sapwood area index (22%), and a 20% decrease in total leaf area index after the fire (Gharun *et al*. 2013a). After 3 years, the canopy in the regrowth forest closely resembled those of mature forests and, as such, stand water use in the regenerating forest should not increase substantially after this time (Turnbull *et al*. 2014, *in review*). Our results provide valuable information about the effects of fires on the water use of mixed-species forests in south-eastern Australia. This knowledge can be used in forest water use models and to inform management decisions for the south-eastern Australian mixed-species forests.

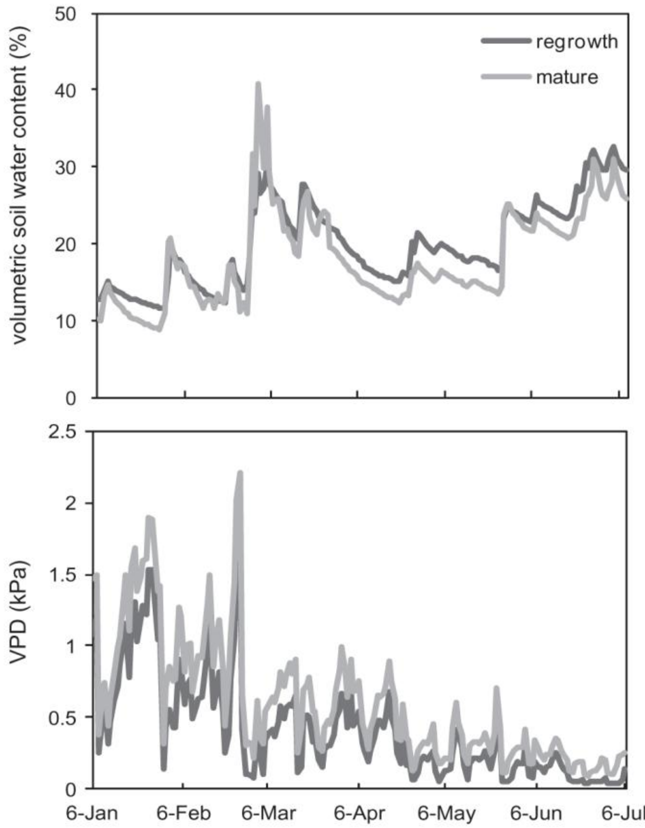

Figure 1. Comparison of average daily volumetric soil water content (top panel) and daily vapour pressure deficit (VPD; bottom panel) at regrowth and mature sites during January to July 2012 (from Gharun *et al*. 2013b).

Future research

We have characterised patterns of water use in three tree species that regenerate from fire by sprouting epicormic branches. It should be noted that the period for which this project was undertaken (2010-2012) was wetter than average (see Gharun *et al*. 2013b). Thus the results we obtained here may not be 'typical' eco-hydrological responses for mixed-species eucalypt forests. The process of regeneration in mixed-species forests is a product of burn severity and weather patterns during the regeneration period. For example, in the mixed-species forests of the Cotter Catchment (ACT), many trees are still epicormic 10 years after fire and the canopies have remained small, often with large dead branches still the highest and widest part of the tree whilst the shrub layer is dense and well-developed (Adam Leavesley, ACT Parks and Conservation Service, pers. comm. 2013).

Now that we have produced and tested models in mixed-species forests (Buckley *et al*. 2012) that are able to be parameterised using short campaigns (no longer than 4 weeks), it would be a straightforward exercise to characterise and predict water use in mixed-species forests across a range of burn severities, eucalypt species, post-fire weather patterns and landscape topographies.

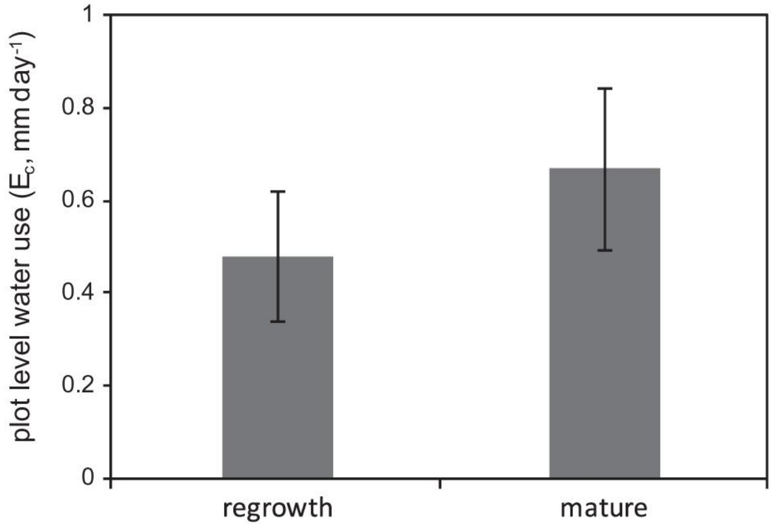

Figure 2. Basal area (m^2 ha^{-1}) and the contribution of trees with DBH <10 cm to total basal area for each site (from from Gharun *et al*. 2013b).

End User interaction

As with other Fire in the Landscape projects, there has been continued interaction with End Users throughout the life of the project. This was in the form of input into quarterly reports and other milestone documents, regular face-to-face meetings with the Lead End User and oral and poster presentations at Research Advisory Forums and Bushfire CRC conferences. In addition, a field trip to showcase the two water-related projects being done by the University of Sydney and the University of Melbourne was organised for End Users in March 2012.

Tarryn Turnbull led the first part of the tour visiting the high-altitude mixed-species forest site near Stanley that was burnt in the Black Saturday fires in 2009. She described the forest type, the way it regenerates after a fire, and the link between vegetation water use and catchment water yield. The overall design of the experiment and a description of findings to date were presented to End Users before moving to the mid-elevation site. Michael Kemp demonstrated the infrastructure necessary to make measurements of tree water use and the lengths we have to go to prevent their degradation by local vermin (Fig. 3).

Figure 3. Michael Kemp describes the equipment used in the project during an End User field trip.

Outputs

Publications

Buckley TN, Turnbull TL, Adams MA (2012) Simple models for stomatal conductance derived from a process model: cross-validation against sap flux data. *Plant Cell and Environment* 35: 1647-1662.

Gharun M, Turnbull TL, Adams MA (2013a) Validation of canopy transpiration in a mixed-species foothill eucalypt forest using a soil–plant–atmosphere model. *Journal of Hydrology* 492: 219-227.

Gharun M, Turnbull TL, Adams MA (2013b) Stand water use status in relation to fire in a mixed-species eucalypt forest. *Forest Ecology and Management* 304: 162-170.

Turnbull TL (2012) Quantifying the impact of fire on tree water use. Bushfire CRC Fire Note 115.

Turnbull TL, Buckley TN, Barlow AM, Adams MA (2014) Anatomical and physiological regulation of post-fire carbon and water exchange in canopies of two resprouting *Eucalyptus* species. *Forest Ecology and Management* (*in review*).

International conference presentations

Gharun M, Turnbull TL, Adams MA (2012) Post fire water use dynamics in mixed-species eucalypt forests. IAHS ICCE Conference on Wildfire and Water Quality, Banff, Canada.

Turnbull TL, Buckley TN, Adams MA (2012) Canopy re-establishment and leaf physiology of resprouting eucalypts after wildfire. IAHS ICCE Conference on Wildfire and Water Quality, Banff, Canada.

Project 2: Quantifying risk of water quality impacts from burned areas

Research institute: Department of Forest and Ecosystem Science, University of Melbourne
Researchers: Pat Lane, Gary Sheridan, Petter Nyman, Philip Noske, Chris Sherwin
Collaborators and affiliations: Owen Jones, Department of Mathematics and Statistics, University of Melbourne; Pete Robichaud, US Forest Service; Sue Cannon, US Geological Survey

Project summary

Fire poses an immediate threat to the water supplies of towns and cities because water treatment facilities in south-eastern Australia (and often in other parts of Australia) are designed to treat relatively clean water from unburnt forested catchments. For example, following the 2003 fires, Bendora Reservoir (Canberra's water supply) experienced turbidity values 30 times the previously recorded maximum, forcing water restrictions on the Canberra and the Australian Capital Territory (White *et al.* 2006). Melbourne's water supply is also at risk, with approximately 80% of the city's water sourced from the (forested) Upper Yarra and Thompson catchments, with minimal treatment capacity.

In the last decade, post-fire debris flows have been identified as a key erosion process following fire and in south-eastern Australia, the significance of debris flows generated from convective storm events has only recently been recognised as a risk to water quality (Sheridan *et al.* 2009; Nyman *et al.* 2011; Smith *et al.* 2011). However the magnitude of the risk to water quality (i.e. the probability of interruption to water supplies) and the degree to which this risk is modified by management actions (e.g. prescribed burning) is unknown.

The *scientific* aim of this research is to quantify the relationship between burn severity and the probability of water quality impacts in excess of water treatment thresholds in Australian catchments. The methods include model development, survey of extreme erosion events and field experiments to quantify the relationships between fire severity and hillslope hydrologic and erosion properties. The *management* aim of this project is to help fire managers answer the question "What are the real risks to uninterrupted water supply if this catchment is burnt by wildfire, and can I reduce this risk with prescribed fire?"

A priori state of knowledge

A general distinction can be made between model structures which predict magnitude of response and those that predict the frequency of response. Models of event magnitude are concerned with how rainfall on burnt catchments translate to a response, and they use information on fire severity, the landscape, and rainfall conditions to predict the magnitude of some response variable such sediment yield or peak discharge (Robichaud *et al.* 2007; Cannon *et al.* 2010; Moody 2012). Models of event frequency on the other hand are concerned with the frequency and intensity with which fire and rainfall overlap with the landscape in space and time (Benda and Dunne 1997; Istanbulluoglu *et al.* 2004).

Existing modelling tools are concerned primarily with predicting event magnitude *after* a fire has occurred (i.e. the catchment conditions and the fire event are given). The challenge is to understand fire impacts on soil and being able to model the connectivity between hillslopes and drainage networks for different fire severities. At this temporal scale of modelling there is a "window of risk" (Prosser and Williams 1998) for several years within which severe erosion events may occur, depending on whether a storm of sufficient magnitude overlaps with the burnt area. When a storm does occur in a burnt area, the magnitude of the erosion event is determined through response models, which incorporate many factors including soil properties, topography, and the fire impact (the departure from background conditions). Models that quantify risks during a "window of disturbance" are by definition restricted to within-burn time scales and not designed to represent both fire and rainfall regimes as variable and non-stationary components of risk.

However, both fire and rainfall regimes vary spatially and are sensitive to changing climate (Hennessy *et al.* 2005; Bradstock *et al.* 2009). Furthermore, fire regimes can be modified directly through fuel management and suppression (Cary *et al.* 2009; Price and Bradstock 2011). Predicting the geomorphic and hydrological response of forested systems to such changes in landscape processes is important for understanding disturbance regimes and geomorphic processes in forested catchments (Dale *et al.* 2001; Istanbulluoglu *et al.* 2004). Predicting the frequency and magnitude of events under variable fire and rainfall regimes involves capturing the nature of the spatial and temporal intersection between the causes of risk: fires and rainfall events. Modelling tools and a conceptual framework is lacking when it comes to quantifying this intersection.

In this project we ask the questions:

1. What is the first-order effect of the spatial-temporal overlap between fires and storms on erosion?
2. How does this first-order effect translate to erosion response in landscapes with variable topography, soils and burn properties?

Research results

The project consisted of three key research components:

- First we developed a model that represents fire and rainfall regimes as variables which influence the overall risk of water contamination.
- In the second phase we couple data on post-fire erosion processes with measures of landscape aridity to develop a basis for modelling variation in catchment responses to fire of different severities.
- In a third (and ongoing) phase we use landscape scale quantification of erosion response in areas burnt by wildfire and prescribed fire to evaluate the probability of extreme erosion following burning at different intensities.

The key activities during different stages of the project are listed in Table 2.

Table 2. Timeline of key activities.

Key activities	2010-2011	2011-2012	2012-2013	2013-2014
Literature review				
Model development – Fire and rainfall regimes as drivers of risk				
Source aerial imagery for assessment of debris flow occurrence				
Field surveys to build a dataset for ground validation				
Source data to parameterise coverage model				
Submit journal article describing the model and its parameters				
Submit journal article based on the literature review				
Build a database of debris flow occurrence and predictor variables				
Develop a method for characterising landscape aridity				
Submit journal article on characterising landscape aridity				
Perform analysis on debris flow occurrence				
Submit journal article on predicting debris flow occurrence				
Search for funding to support ongoing post-fire erosion research				
Submit journal article on runoff and erosion process in small headwaters				

Model of fire and rainfall regimes as controls on debris flow frequency

Fire and rainfall processes operate in the landscapes to produce patterns whereby erosion events occur as "episodic patches of activity" (Miller *et al.* 2003). Under this description, the patches are determined by intersection between storms and burnt areas (Fig. 4), and the activity (erosion processes) is determined by landscape attributes and the sensitivity to fire impacts. If one's aim is to predict the likelihood of water quality impact *following* fire then the modelling effort should focus on activity (erosion processes) and how this changes with different rainfall inputs and fire severities. If the aim is to quantify risk within a catchment in the context of, for example climate change, then the focus should be on the interaction between storms and burnt areas. Separating between these different sources of uncertainty is important when moving towards risk-based approaches in wildfire and forest management (Hyde *et al.* 2012).

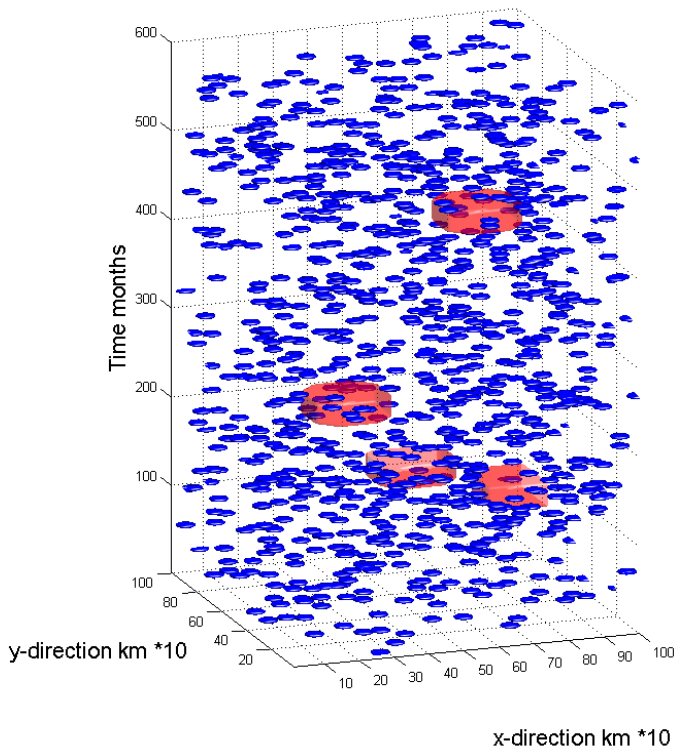

Figure 4. The germ and grain model used to characterise the spatial-temporal overlaps between fire disturbance and rain storms. Fire events and storms represented as red and blue discs respectively. The frequency and size of each event can be determined from statistical records. The model assumes that location of events is random and that events are independent from one another(Jones *et al.* 2011; Jones *et al.* in review).

Germ and grain models can provide a powerful framework within which the intersection of burnt areas and storms can be quantified. The expected area of intersection is a measure of event frequency that is independent of the landscape vulnerability and the sediment transfer processes that occur following fire. It represents the average annual area where fire and rainfall satisfy the conditions known to be required for high-magnitude erosion events to occur in a particular landscape (Fig. 5). In our research, we were specifically interested in debris flows in Eucalypt forest of south-eastern Australia and therefore used a known half-hour rainfall threshold for post-fire debris flow initiation as a response threshold (Fig. 5).

We restricted the coverage model to represent debris flow processes in the first year after wildfire. Parameters for rainfall and fire regimes controlling debris flow frequency were obtained using rainfall data from the Bureau of Meteorology and fire history data for Canberra and Victoria (Table 3). Other parameters apply for different environments and processes. Assuming a vulnerable landscape where all these potential erosion events actually occur, and given an estimate of the size of these erosion events, we can calculate the annual average sediment load from the particular processes being considered in the coverage model. Essentially the model output is a function of both the coincidence of burnt areas and storms (patches or intersections) and the vulnerability of the landscape (erosion and sediment transfer processes).

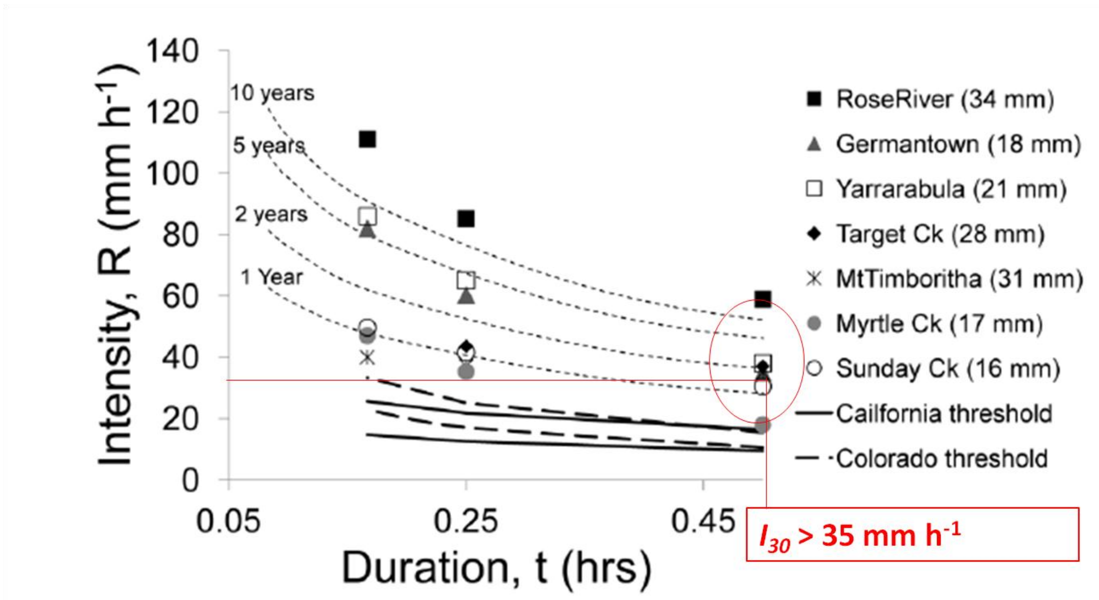

Figure 5. Debris flow triggering rain storms in the eastern uplands of Victoria. The sites are located in areas that were burnt in the 2007 and 2009 wildfires. All debris flows occurred within the first year since the fire. The return intervals shown in Fig. 6 are representative of Bright in north-eastern Victoria.

Table 3. Storm and fire regime parameters for debris flow-prone regions in south-eastern Australia.

Location	Storm event rate[a] $\times 10^{-2}$ μ *km^{-2} year^{-1}*	Storm size $\times 10^{-4}$ β *km^{2} *year*	Fire event rate $\times 10^{-4}$ λ *km^{-2} year^{-1}*	Fire size α *km^{2} *year*	Fire event rate with climate change (2050)[b] $\times 10^{-4}$ λ_{cc} *km^{-2} year^{-1}*
		Victoria			
Licola	3.20				
Bright	4.27	5.7	0.941	201	1.13 – 1.74
Kilmore	1.96				
		Australian Capital Territory			
Namadgi NP	2.85	5.7	1.850	67	2.22 – 3.42

The risk model has a number of applications. To quantify the effect of climate change on the risk of high-magnitude erosion events, we need to quantify the effect of climate change on fire and storm regimes. In this paper we modelled the effect of climate change on fire frequency and used this to evaluate climate change effects on erosion regimes in different rainfall regimes. This approach could be extended to include climate change effect on fire-size and storm frequency. Another immediate application of the model is to quantify the effect of controlled burns. That is, we consider fires to be either low-impact prescribed burns or high-impact wildfires, each with their own frequency and size parameters. As the frequency of prescribed burns increase, the frequency of wildfires will reduce (e.g. Bradstock *et al.* 2012). Provided we can quantify the relative frequencies of prescribed burns and wildfires, we can use the model to quantify the change in the risk of high-magnitude erosion events.

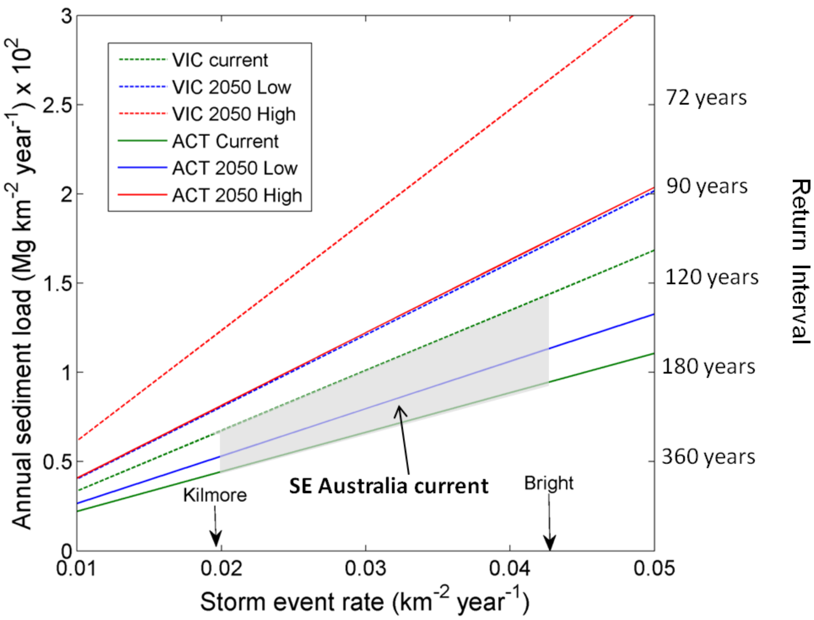

Figure 6. Annual average sediment load from runoff generated debris flows in south-eastern Australia as a function of storm event rates and for current and future wildfire regimes. Event-based sediment loads obtained from Nyman *et al*. (2011). High and low climate change impacts correspond with lower and upper bounds of the range of impacts from Bradstock *et al*. (2009).

Linking variation in runoff and erosion processes to landscape aridity and fire severity

In this project component we were interested in using aridity index as a way to characterise landscape variability in post-fire erosion response. Landscape aridity influences vegetation structure, soil production and fire regimes, and is important for water and carbon dynamics at global, regional and local scales. Globally, the effect of landscape aridity is apparent as a gradient in productivity going from rainforest to deserts. At local scales, the effects are apparent as distinct shifts or gradients in ecosystems and catchment processes. Different indices are used to quantify aridity but in general they reflect the long term balance between precipitation and potential evapotranspiration (PET) or net radiation. Aridity is commonly calculated at a point and interpolated to regional scales using long term precipitation records and measurements of PET at multiple points distributed in the landscape. Spatial interpolation however fails to take into account the local effects of clouds and small scale topography on net radiation which can cause large variability in aridity, particularly in mountainous terrain.

We developed a novel method for combining satellite measurements and topographic downscaling to model spatial variability in aridity. Regional data on radiation (derived from satellite data), temperature, cloud fraction and precipitation was obtained from the Bureau of Meteorology and coupled with a topographic downscaling algorithm to produce estimates of net radiation and aridity at the resolution of a 20 m digital terrain model. Results show that annual precipitation (and cloud fraction) gradients drive the variability in aridity at large scales (10-100 km) while small scale (e.g. 1 km) topographic characteristics (e.g. slope aspect and slope angle) are the main drivers at local scales. The aridity index was observed at low values on southern aspects and high values on northern aspects (Fig. 7).

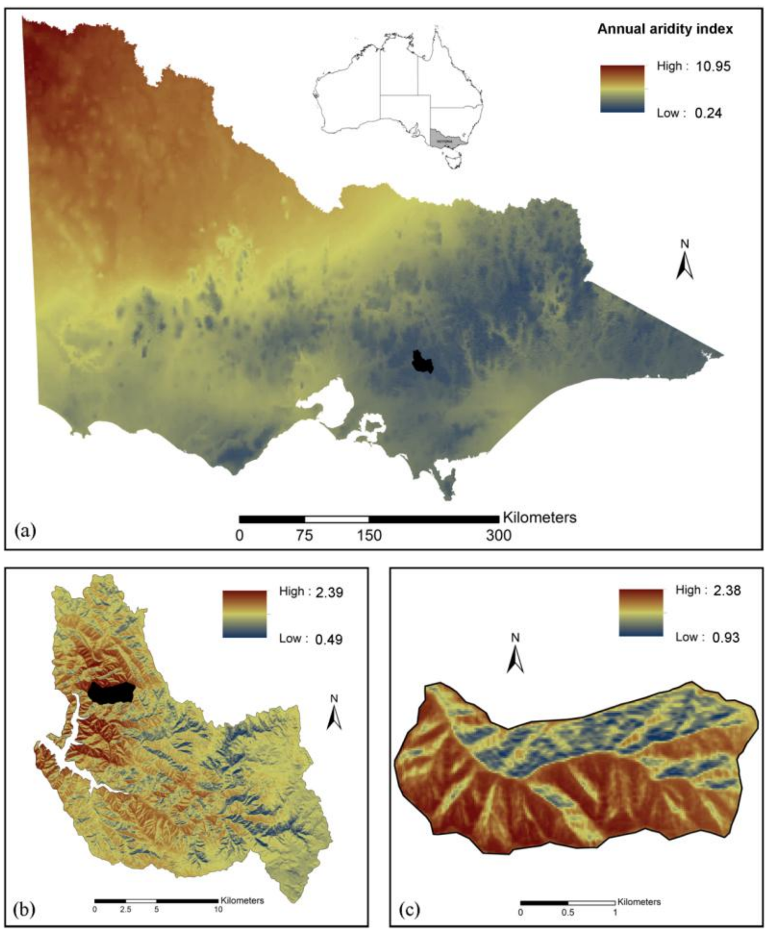

Figure 7. Landscape aridity at different scales: (a) state-wide (Victorian) variability, (b) catchment-scale variability, and (c) local variability.

Field experiments in small headwater catchments (<1 ha) were used to evaluate how runoff and erosion processes vary depending on landscape aridity and fire severity. Previous research from the south-eastern Australian region and elsewhere indicate that these two factors are important in creating variability in the magnitude of responses measured from burnt areas.

Catchments were instrumented so that there were three levels of fire impacts (wildfire, prescribed fire and unburnt) and two levels of aridity (Table 4). The two levels of aridity were obtained by locating the sites in different aspects. This means that there were only slight differences in aridity. Future experiments will aim to incorporate a wider range of aridity values in the post-fire monitoring. The sites in wildfire affected areas were instrumented following the 2009 wildfire in Victoria. Sites in unburnt and prescribed fire areas were instrumented in 2011. The aim was to measure the production of runoff and sediment continuously over a 3 year recovery period. The instrumentation consisted of a rain gauge for measuring rainfall, a sediment trap and a large tipping bucket for recording runoff rates (Fig. 8). Rainfall and runoff were measured at 3-minute time intervals.

Table 4. The combination of sites and 'treatments' in small headwater monitoring study.

	North (dry)	South (less dry)
Wildfire	×	×
Prescribed fire	×	Not yet
Unburnt	×	×

Figure 8. Sites and 'treatments' in small headwater monitoring study. The sites are located in catchments near Myrtleford in north-eastern Victoria. The wildfire sites featured in the Bushfire CRC field excursion in March 2010.

The monitoring of the headwater catchments is ongoing. The systems are still recovering and we are looking at funding opportunities for continuing and expanding the monitoring and capture data from sites in wetter forest types. The runoff data for the first year of monitoring is shown for four sites including north- and south-facing aspects in wildfire affected sites and north-facing sites in forests that were unburnt or burnt by prescribed fire (Fig. 9). For wildfire-affected sites, there was a sharp increase in runoff production once the rainfall intensity exceeds 10 mm h^{-1}. In the catchment burnt by prescribed fire, the sharp increase occurred at higher rainfall intensities (30 mm h^{-1}). Unburnt sites displayed only a modest runoff response even with rainfall intensities of 40 mm h^{-1}, supporting the notion that undisturbed catchments are unlikely to result in large erosion events during storm events.

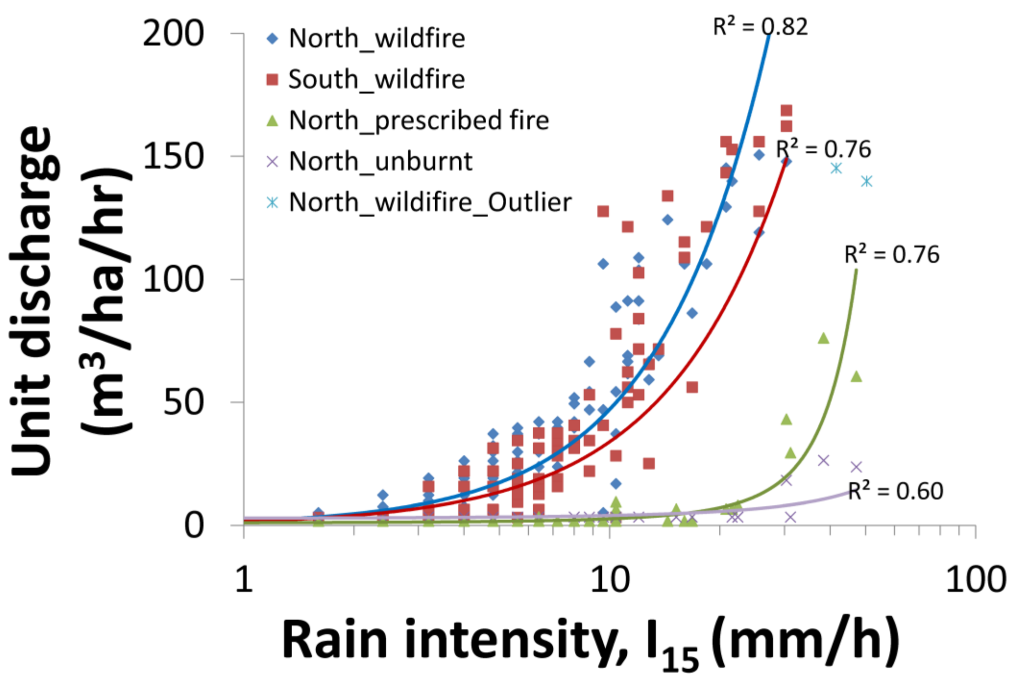

Figure 9. The relationship between unit discharge (m^3 ha^{-1} hr^{-1}) and 10-minute rainfall intensity, I_{15} (mm hr^{-1}), in the first year after prescribed fire and wildfire. The unit discharge is a measure that can be used to model how responsive different landscape units are after burning at different intensities.

Landscape-scale response to wildfire

The aim of this third research component was to develop a model which quantifies the likelihood of debris flows as a function of landscape position, slope and fire severity in the contributing area, and rainfall intensity. The first step in this analysis was to build a data set for ground-truthing aerial photography interpretations (Fig. 10). The level of accuracy in aerial imagery interpretation was quantified by statistical comparison of debris flow measurements in field surveys and aerial imagery.

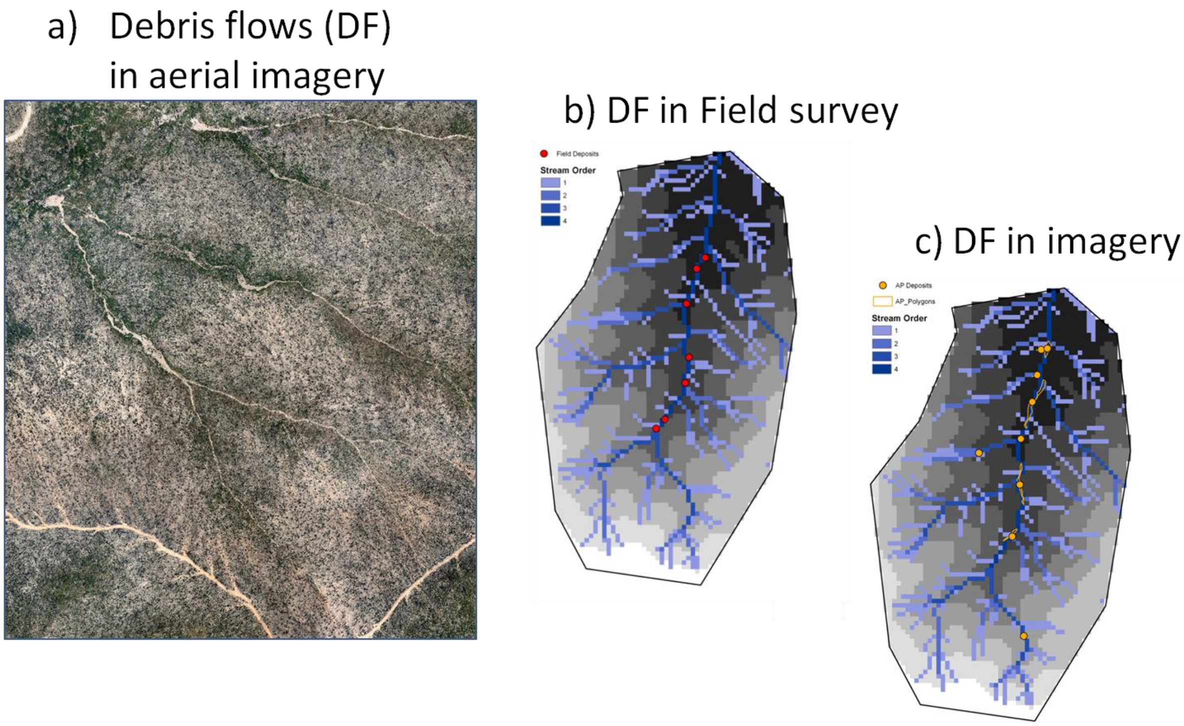

Figure 10. (a) A debris flow event visible in aerial imagery at Myrtle Creek in the Beechworth fire. (b) The location of debris flow deposits (red dots) in field surveys of the Stony Creek catchment near Myrtleford. (c) The same catchment, but with the location of debris flow deposits (orange dots) determined from imagery.

The location of debris flows were used to draw a drainage network in the Beechworth fire with information on whether or not a drainage line was affected by debris flows (Fig. 11). This network can be used to develop a statistical model of debris flow occurrence. Initially we included aridity index, slope, 30-minute rainfall intensity and fire severity as predictors of debris flow occurrence. Slope and landscape aridity emerged as the most important predictors in the preliminary analysis of the data. The analysis was performed on areas burnt by the Kimore – Murrundindi fire and the Beechworth fire. Additional predictive power can be achieved in the by including survey data from prescribed burns in the analysis. The inclusion is dependent on the availability of additional funding after the end of the current Bushfire CRC.

Future research

The project with the Bushfire CRC has contributed to the state of knowledge in two key areas. The first and perhaps the most significant contribution is the progress on the conceptual representation of fire disturbance in models of catchment processes. The review paper (accepted) on hydro-geomorphic response models for burnt catchments and the paper (in review) on the coverage model represent important contributions in terms of how post-fire catchment processes can be quantified consistently and systematically in a risk-based framework. Building on this work to incorporate local landscape conditions in the proposed modelling framework is a logical next step in terms future research and data collection. The work should aim to characterise local rainfall and fire regimes as well as the sensitivity of the landscape to these processes. Sensitivity will vary from region to region depending on vegetation characteristics, soil properties and topography.

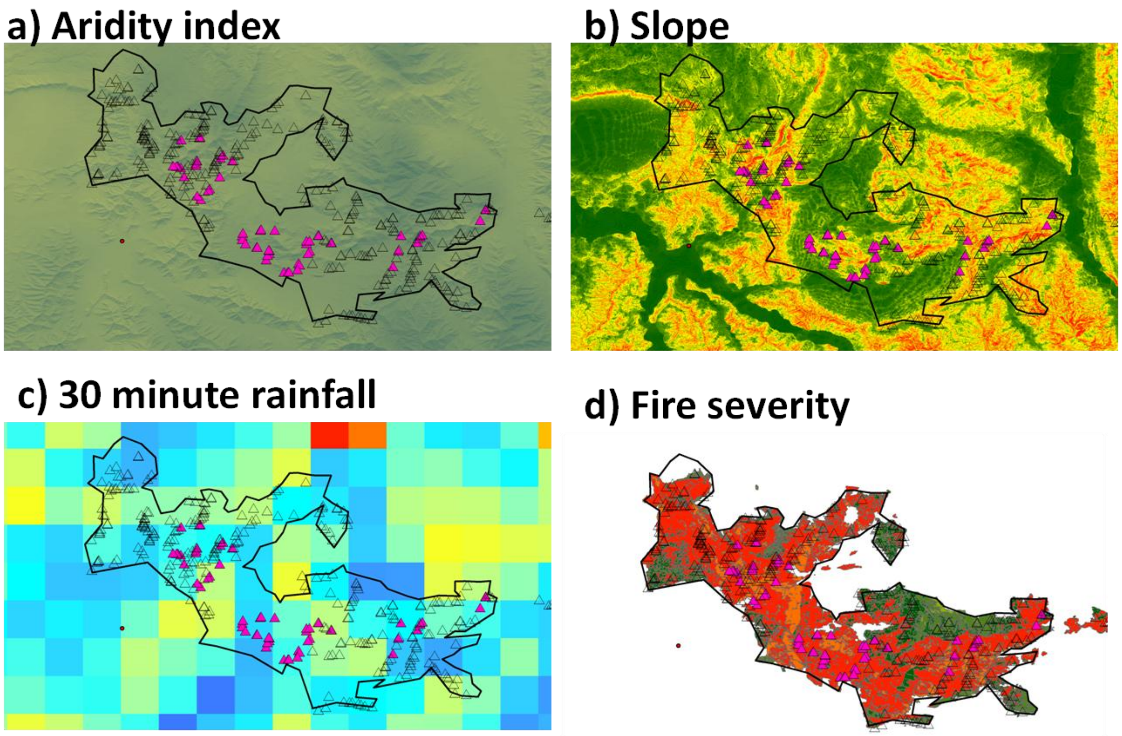

Figure 11. Debris flow locations (pink marks) in relation to (a) aridity, (b) slope, (c) 30-minute radar rainfall and d) fire severity. Debris flow occurrence can be analysed in a logistic regression with these variables as predictors.

Understanding and quantifying all the factors that contribute to sensitivity is a large undertaking. In this project we used the 2009 wildfires in north-eastern and central Victoria as an opportunity to build a dataset on post-fire response and landscape sensitivity to wildfire in this particular region. These wildfires were coupled with experiments in prescribed fires in the same region in order to evaluate the relative response of the landscape to high and low severity burns.

Much more research is required to understand the full interaction between fire severity and landscape properties across regions with different landforms, geology and vegetation characteristics. Collecting this data is resource intensive and likely to require ongoing funding from land management agencies within the respective regions and collaboration with local research agencies. Australia should look to the US and the role of federal agencies such as the US Forest Service in terms of the systems they have put in place for (i) collecting data on post erosion processes and (ii) conducting assessments of post-fire catchment risk. Collecting data on post-fire runoff and erosion responses should be placed alongside other ecosystem values and considered as part of routine-based evaluation of fire impacts on the landscape.

End User interaction

Communication with End Users has been ongoing during all stages of the project. Quarterly meetings, listed as milestones, have been important in our interaction with End Users. In the early stages of the project, these meetings provided an opportunity to discuss our research approach and finding areas where research question overlap with the key demands from land managers. This type of interaction has had an important role in project development stage in that it has helped ensure that our research objectives were aligned with the expectation of the agencies.

Discussion papers have lead to some interesting dialogue with the Lead End User regarding the needs of land managers in relation to the scientific issues underlying the research questions. The questions that intrigue the researcher might not be that relevant to the needs of land managers. The discussion papers helped build awareness around this issue.

A field excursion to the research site in March 2012 provided an opportunity to discuss our research and share ideas with representatives from different End User groups. We described our research site and current findings to the Bushfire CRC management team and End User representatives from Melbourne Water, DSE and other land management agencies.

In terms of research uptake, there has been some important contribution by our research team to the development of algorithms for assessing post-fire catchment risk. The algorithms were developed to assist the Bushfire RRATs in Victoria with their evaluation of flooding and water quality risks in areas burnt by wildfire (Fig. 12). The algorithms draw in part on the research conducted by the Bushfire CRC researchers at the University of Melbourne. The data produced as part of the debris flow mapping work with the Bushfire CRC, will be used to revisit and improve some of the risk algorithms currently used by the RRATs. The aim is to integrate water quality risks with debris flow occurrence and to develop more quantitative measures of actual debris flow probability. There are opportunities to develop additional tools which, for instance, can help determine where and where not in the landscape to apply prescribed fire. The capacity of the research team to translate specific research finding into tailored management tools for the agencies depends somewhat on the availability of funding and will need to be considered on a case by case basis.

As the Bushfire CRC-funded research is coming to an end it is important that it is not the end of the interaction with the agencies have had inputs to the project. There has been a strong sense of enthusiasm amongst End Users for our research and we look forward to continued communication with agencies to support informed decision making around the issue of fire effects on landscapes. Successful research utilisation is not just about what is gained (or adopted) from 2-3 years of research, it is also about building effective and sustainable basis for communication between researchers and End Users.

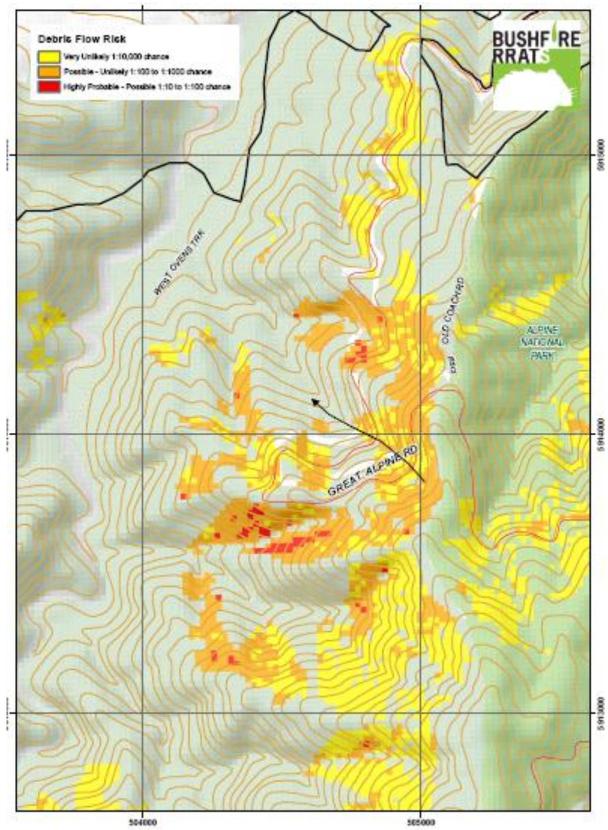

Figure 12. A map of debris flow risk in the East Ovens River near Harrietville which was burnt by wildfire in February 2013. The risk was determined using algorithms developed from post-fire erosion research by the University of Melbourne and the Bushfire CRC (Sheridan *et al.* 2011).

Outputs

Publications

Cawson J, Sheridan GJ, Smith HG, Lane PNJ (2011) The effect of prescribed fire severity and burn patchiness on runoff and erosion. In: Proceedings of the AFAC and Bushfire CRC Conference Science Day, RP Thornton (Ed.), Sydney.

Cawson JG, Sheridan G J, Smith HG, Lane PNJ (2012) Surface runoff and erosion after prescribed burning in forests and the effect of difference fire regimes: a review. *International Journal of Wildland Fire* 21, 857-872.

Jones OD, Nyman P, Sheridan GJ (2011) A stochastic coverage model for erosion events caused by the intersection of burnt forest and convective thunderstorms. 19th International Congress on Modelling and Simulation, Perth.

Lane PNJ, Sheridan GJ, Noske PJ, Sherwin CB, Costenaro J, Nyman P, Smith HG (2011) Fire effects on forest hydrology: lessons from a multi-scale catchment experiment in SE Australia, paper presented in Revisiting Experimental Catchment Studies in Forest Hydrology, Proceedings of a Workshop held during the XXV IUGG General Assembly, Melbourne.

Nyman P, Sheridan GJ, Jones OD, Lane PNJ (2011a) Erosion and risk to water resources in the context of fire and rainfall regimes. In: Proceedings of the AFAC and Bushfire CRC Conference Science Day, RP Thornton (Ed.), Sydney.

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Nyman P, Sheridan GJ, Lane PNJ (2013) Post-fire response models and their applications in hazard prediction and land management. *Progress in Physical Geography* (*accepted*).

Jones OD, Nyman P, Sheridan GJ (2014) Modeling the effects of climate change on extreme erosion events in forests. *Stochastic Environmental Research and Risk Assessment* (*in review*).

Nyman P, Sheridan GJ, Smith HG, Lane PNJ (2014a) Modelling the effects of surface storage, macropore flow and water repellency on infiltration after wildfire. *Journal of Hydrology* (*in review*).

Sherwin CS, Nyman P, Langhans C, Sheridan GJ (2014b) Combining satellite measurements and topographic downscaling to model variability in net radiation and aridity index. *Australian Meteorological and Oceanographic Journal* (*in review*).

National and international conference presentations

Jones OD, Nyman P, Sheridan GJ (2011) A stochastic coverage model for erosion events caused by the intersection of burnt forest and convective thunderstorms. 19th International Congress on Modelling and Simulation, Perth.

Nyman P, Jones OD, Sheridan GJ (2013) Modeling the effects of climate change on extreme erosion events in forests. European Geophysical Union, General Assembly.

Nyman P, Sheridan GJ, Jones O (2011) A model for predicting erosion under variable fire and rainfall. Seminar Series Fall 2012. Colorado University, Colorado

Nyman P, Sheridan GJ, Moody JA, Noske, PJ, Lane PNJ, Smith HG (2013) Modeling the effects of climate change on extreme erosion events in forests. European Geophysical Union, General Assembly.

Nyman P, Sheridan GJ, Moody JA, Smith HG, Lane, PNJ (2011) Depth-dependent erodibility: representing burnt soils as a two-layered cohesive/non-cohesive system. American Geophysics Union, Fall Meeting, the Moscone Convention Center, San Francisco, California.

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Sheridan GJ, Nyman P, Jones OD (2011) A stochastic germ-grain model to estimate wildfire induced debris flow risks in a changing climate. American Geophysics Union, Fall Meeting, the Moscone Convention Center, San Francisco, California.

Project 3: Environmental impacts of prescribed and wildfire – emissions management

Research institute: Department of Forest and Ecosystem Science, University of Melbourne
Researchers: Chris Weston, Luba Volkova
Collaborators and affiliations: Department of Sustainability and Environment Victoria, Tasmanian Parks and Wildlife Service, Queensland Parks and Wildlife Service, Department of Water and Natural Resources SA, ACT Parks and Conservation Service

Project summary

This project measured forest carbon stocks and the impact of planned fire on these stocks through release of greenhouse gases to the atmosphere and redistribution of carbon within the forest. The study sites covered a range of southern *Eucalyptus*-dominated forests across five states. Assessments of forest carbon in aboveground biomass, dead wood, litter and in soil before and after prescribed burning formed the basis for calculation of fire-induced loss of carbon to the atmosphere and of carbon redistribution in the forest. Modelling of carbon losses from each pool affected has been determined. Results of this project will help forest managers and policy makers to predict fire impacts on carbon losses and the magnitude of greenhouse gas emissions over a range of forest types and burn conditions. Knowledge from this project will enable fire managers to achieve fuel reduction targets whilst minimising greenhouse gas emissions to the atmosphere.

A priori state of knowledge

Planned fires over large forest areas are essential to reduce the risk of large-scale bushfires in forests near population centres and important forest assets such as water catchments and commercial plantations. However, planned fires release emission and reduce forest carbon stock (North and Hurteau 2011). It has been widely recognised that planned fires reduce loads of litter (i.e. dead partly decomposed organic material on the forest floor), yet fire impacts on other major carbon pools such as overstorey trees, shrubs, ground cover, coarse woody debris and soil organic matter is not well documented for southern Australian forests. For these forests, fragmented data is available for fire impact on understorey vegetation (studies from Western Australia, Sneeuwjagt and Peet 2004; Gould *et al*. 2007); elevated bark (study from Victoria, Tolhurst 1994) and coarse woody debris (CWD; mainly in wildfires, Hollis *et al*. 2011). However, fire also modifies forest organic matter to produce a wide range of charred and partially oxidised materials (Andreae and Merlet 2001). The accession of burnt organic matter to the soil surface has not been clearly accounted for. A holistic approach for measuring fire-related carbon loss and redistribution among pools for southern Australian forests is lacking. As there is no data available for carbon distribution among carbon pools there is no clear understanding of how burning practices can be modified to minimise carbon losses and emissions.

Several studies of fire-related carbon losses have been conducted in high carbon density wet sclerophyll forests of south-eastern Australia (e.g. Simkin and Baker 2008; Lindenmayer 2009;

Benyon and Lane 2013), yet these forests are not subject to routine planned fires and thus are of little use for land managers in estimating potential mitigation for carbon emissions. A number of studies from Europe and the United States have indicated considerable potential for carbon emission mitigation using planned fires (e.g. Hurteau and North 2009; Vilén and Fernandes 2011). Studies in northern Australia have also identified the opportunities for fire management to reduce emissions and achieve carbon credits for local communities (e.g. Indigenous Land Corporation). Yet the same cannot be said for southern Australian forests where opinion is divided on the opportunity that planned fire presents for mitigating wildfire emissions in the longer term (e.g. Adams 2013) and the perceived immediate negative impacts of broader scale planned burning (e.g. Bradstock *et al*. 2012).

In this project we measured all carbon pools (excluding 'belowground live', Intergovernmental Panel on Climate Change (IPCC) 2006) for a range of dry *Eucalyptus* forests in south-eastern Australia (Victoria, South Australia, Tasmania, Australian Capital Territory, Queensland) before and after planned and unplanned fire of differing intensities. The findings from this project can significantly improve our knowledge of forest carbon balances, the impact of fire on forest carbon stocks and the magnitude of emissions produced during fire.

Research results

Over three years of research we have established 61 study plots in long unburnt *Eucalyptus* forests across five states of south-eastern Australia (Fig. 13). Forest types measured included dry sclerophyll, lowland, open, shrubby dry and coastal forests. Experimental design included establishment of circular sampling plots of 45 m in diameter at each study site and measurements of four major carbon pools: (1) aboveground alive (live overstorey trees, understorey vegetation, elevated fuels); (2) deadwood (stump, dead standing trees, coarse woody debris); (3) litter (dead leaves, bark, twigs and branches on the forest floor with diameter <2.5 cm) and, (4) soil to 30 cm depth, including organic matter. Using standard inventory techniques, we measured forest carbon pools before and immediately after fire.

Trees were measured for diameter and height; fractions of litter, duff and soil were collected and analysed for carbon and nitrogen concentrations. Based on biomass changes, emission of CO_2 and non-CO_2 gases (methane and nitrous oxide) were estimated follow the National Greenhouse Gases Accounting Methodology (Australian Greenhouse Office 2008). Experimental design and sampling protocol are described in details in Volkova and Weston (2013). The timeline of establishment of field sites and sampling periods are shown in Table 5.

Overstorey trees and soil to 30 cm depth are the main carbon pools in forests, followed by dead wood, understorey and litter. While litter remains the major carbon pool affected by fire with an average loss of 4 t C ha^{-1}, combined losses from other carbon pools such as CWD, understorey vegetation, ground cover and bark are equivalent to litter (average 4 t C ha^{-1}, all losses account for redistribution). An increase in almost 4 t C ha^{-1} in the duff layer after fire indicates carbon redistribution to other pools. Because current practises in estimating emission are based on mass difference in litter loads only, our results indicated that almost 30% of emissions from planned fires are not accounted for at the national level.

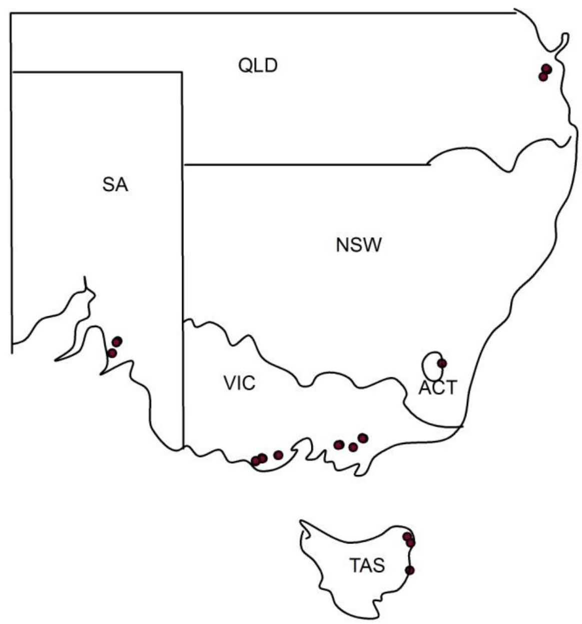
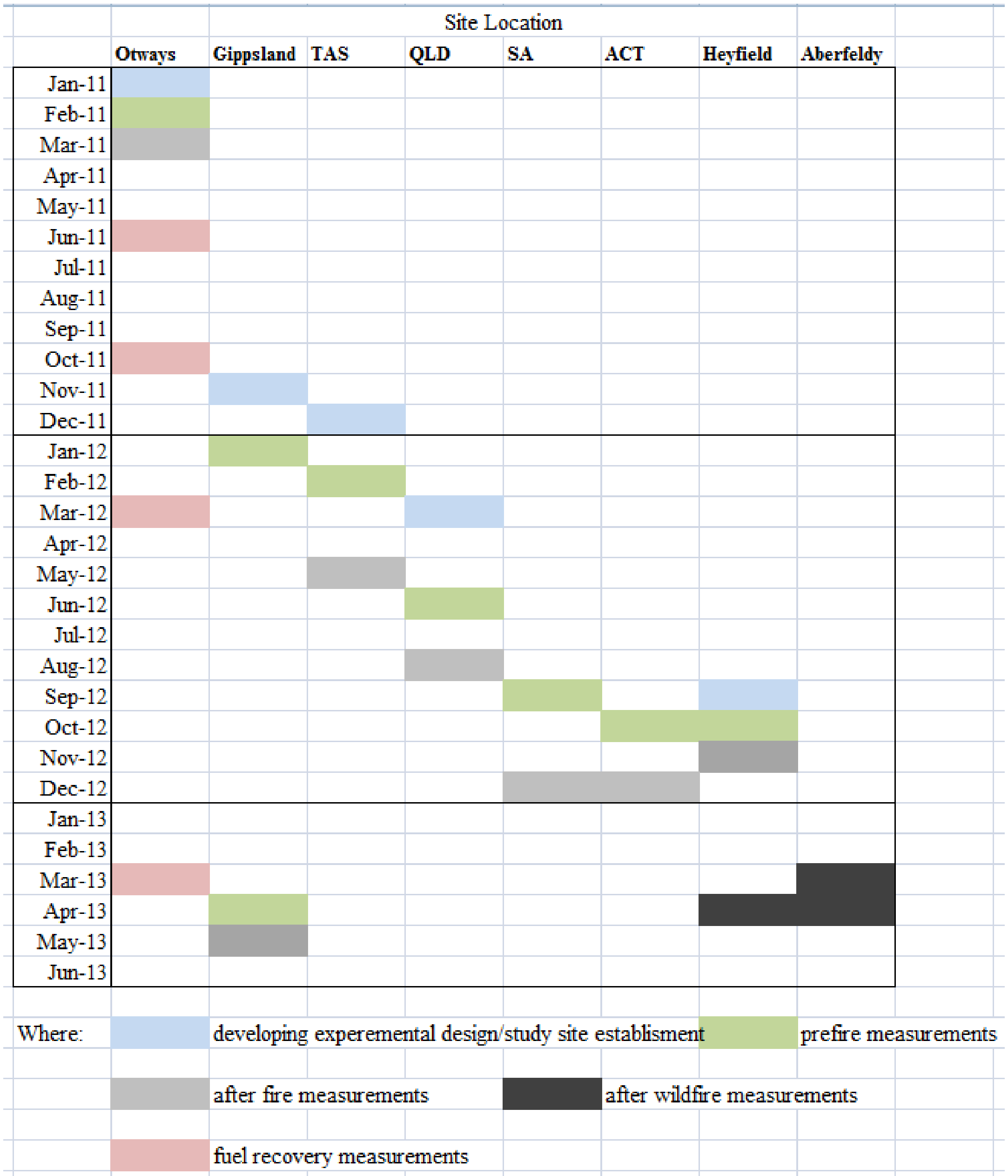


Figure 13. Location of study sites, each dot represents a study plot, n = 61.

As a part of our collaboration with Dr Mick Meyer from CSIRO Marine and Atmospheric Research, we also worked on improving emission factors used in emission estimation as they are an important part of the national greenhouse accounting inventory. Field sampling of smoke at the source of ignition during this project revealed that current emission factors are a factor of 1.5 lower than field-based estimates. This knowledge further contributes to underestimation of fire emission at the national level.

To compare the effects of wildfire and planned fire on forest carbon pools and emissions, a set of study sites were established in wildfire-affected areas in Aberfeldy, Victoria in 2013. The experimental design included three study sites established in long unburnt forest that was subsequently burnt in a wildfire (wildfire-only) and five study sites treated for fuel reduction 3 months prior to the wildfire and re-burnt in the wildfire (fuel-treated). Wildfire-only sites were established in close proximity to fuel-treated ones. We re-measured all carbon pools and soil after the wildfire and compared with pre-fire and after planned fire data. Our preliminary results indicated that planned fire 3 months prior to the wildfire significantly reduced the severity of the wildfire, affecting only forest floor carbon (litter and CWD). Charring of overstorey trees in fuel-treated sites did not exceed 2 m in contrast to complete crown scorch in long unburnt forests. Combined emissions from planned burns and wildfire in fuel-treated forests was half that compared to emissions during wildfire in long unburnt forests.

Table 5. Timeline for establishment of field sites.



Accounting for all carbon losses in fire (planned and wildfire) and applying field-based estimates of emission factors, indicated that, on the national level, we underestimate emission from planned fire by 2.5 times and by 4.4 times for wildfire if default parameters are used (Fig. 14).

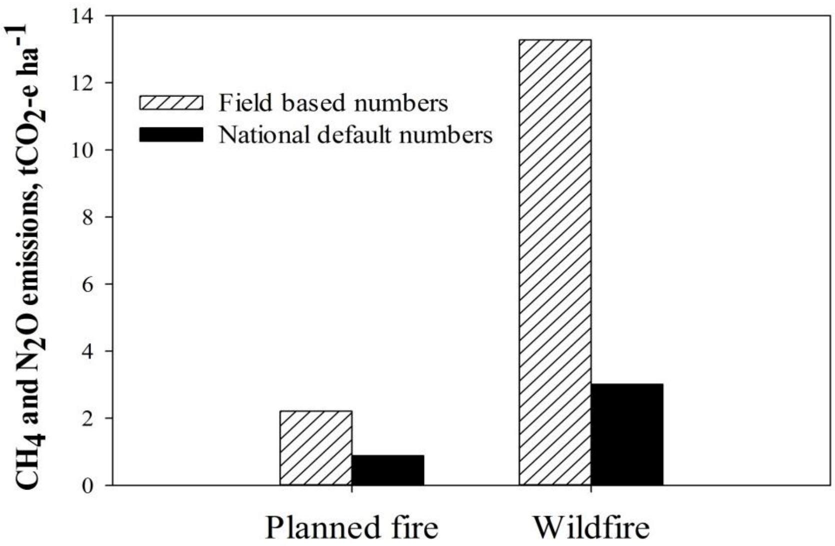


Figure 14. Comparison of non-CO_2 emissions based on field based measurements of affected carbon pools and emission factors and default parameters used in the National Greenhouse Gas Accounting Inventory (Australian Greenhouse Office 2008).

Overall, data analysis has indicated a strong correlation between litter moisture at the time of burning and carbon loss (P = 0.003), with Pearson correlation coefficient, r^2 = 0.42. Model development of the effect of fire on carbon losses as a function of litter moisture is underway. Our research has confirmed the importance of field-based studies and the value of accounting for all carbon pools when estimating fire-related emission. The ability to model all carbon losses and recovery of carbon pools is important to land managers for risk assessment purposes, decision making and for developing emission mitigation initiatives.

Future research

We established that planned fire affects only 2-3% of forest carbon while a further 2% that was formerly considered to have been lost to the atmosphere remained in the forest through redistribution to the forest floor. Remaining challenges include developing landscape scale estimates of forest fuels from forest productivity, including all fuels strata estimates. In correlating forest fuels with forest productivity, the impacts of climate change on fuel accumulation can be predicted to improve management of fire in forests. Another important gap in knowledge is a lack of information on burning efficiency and released emission from coarse woody debris.

End User interaction

The beginning of the project was marked by exceptionally wet summer and autumn seasons across Victoria which prevented us from burning all established plots. In order to continue field-based research within the time frame of the project we had to expand our research to south-eastern Queensland and later to South Australia. These sites were selected, established and measured with the help of End Users in these states.

Our experience in presenting at Research Fora and annual AFAC and Bushfire CRC conferences resulted in close interaction with End Users and their strong interest in the project led to expanding our study sites to Tasmania, Queensland, South Australia and ACT. During the life of the project we had overwhelming support from End Users, such as help with indentifying possible study sites, and providing staff and logistic support for field measurements. Support of End Users led to prioritising established study sites for burns and developed greater awareness about our study sites among the fire crews. Agency staff members were involved in accumulating observations, recording fire behaviour and collection of weather and fuel moisture data. Involving agency staff in field measurements greatly enhanced staff understanding and awareness about of project and importance of this work.

Results of our research have helped End Users to better understand the impact of low intensity planned fire on forest carbon and its emission mitigation potential. Measuring entire forest carbon (from tree canopies to 30 cm soil) has provided End Users with an understanding of carbon distribution in the forest and the knowledge that planned fire releases only a minor fraction of forest carbon (2-5%) to the atmosphere. Our project results have given End Users confidence that a solid scientific basis has been developed and can be used to defend the use of planned burning against negative public perception. The protocols developed for measuring forest carbon and the training of field crews in taking measurements has significantly enhanced the ability of agencies to perform this type of work if required. Our published data have been incorporated into national carbon accounting model, thereby improving national estimates of greenhouse gases emission from planned burning and wildfires. Therefore, our research has yielded data for use at land management level all the way through to a national level.

This project has indentified knowledge gaps in estimating carbon emissions from fire and our limited ability to accurately predict forest carbon consumption. Ongoing interaction with End Users indicates that this work needs to be continued in order to move to the next step: modelling of fuel loads for specific forest types and fire emission based on empirical data. During the life of the project we have presented results to a range of interested End Users and we have been encouraged that there is more scope for further efforts to promote the results of the project. Web-based presentation of seminars and electronic dissemination of information along with training and education of agency staff in key results from our project could be useful aspects for further End User interaction.

Outputs

Publications

Volkova L, Meyer M, Murphy S, Fairman T, Reisen F, Weston C (2014) Fuel reduction burning mitigates wildfire impacts on forest carbon and greenhouse gas emission. *International Journal of Wildland Fire* (*in press*).

Volkova L, Weston C (2013a) Redistribution and emission of forest carbon by planned burning in *Eucalyptus obliqua* (L. Hérit.) forest of south-eastern Australia. *Forest Ecology and Management* 304, 383-390.

Volkova L, Weston C (2013b) Measuring forest carbon and fire emission from southern *Eucalyptus* forests: key findings and some lessons learnt. In: Proceedings of the 2013 AFAC and Bushfire CRC Conference Research Forum. Ed. LJ Wright, pp. 149-160. Melbourne, Australia.

Volkova L, Weston C (2014) How much carbon is really lost in forest fires: findings from 40 Eucalyptus forests of Australia (*in review*).

National and international presentations

Volkova L, Weston C (2011) Impact of fuel reduction burning on carbon balance in *Eucalyptus* forests of south-eastern Australia. Mega Fire Reality International Conference, Tallahassee, US.

Volkova L, Weston C (2012) Impact of fuel reduction burning on carbon balance in *Eucalyptus* forests of south-eastern Australia. Queensland South-Eastern Biodiversity Consortium,

Volkova L, Weston C (2013) Impact of fuel reduction burning on carbon balance in *Eucalyptus* forests of south-eastern Australia. North American Forest Soils Conference, Whitefish, Montana, US.

Project 4: Greenhouse gas emissions from fire and their environmental effects

Research institute: Faculty of Agriculture and Environment, University of Sydney
Researchers: Tina Bell, Malcolm Possell

Project summary

Fire directly impacts the carbon balance of forests through emissions of CO_2, volatile organic compounds and other greenhouse gases formed during combustion of vegetation and litter. We currently lack all but the most rudimentary knowledge of the direct effects of fuel reduction fires or their secondary effects on ecosystem carbon balances. Consequently, we have very little empirical data to model carbon losses during fire.

Our research aims to further develop our knowledge of greenhouse gas emissions from fuel reduction fires and their potential impacts on the carbon balance of forested ecosystems. We will use this knowledge to provide guidelines and advice as to how best to manage these fires to minimise their ecological and economic impacts. This is an important area to investigate as the 'carbon' costs of fuel reduction fires are yet to be determined and will likely have considerable economic value in future.

A priori state of knowledge

Vegetation fires inevitably lead to the production of smoke. Smoke from bushfires and planned burning affects the atmosphere through the production of trace gases (defined as a gas that makes up less than 1% by volume of the atmosphere of the Earth) and aerosols (defined as a suspension of fine solid particles or liquid droplets in a gas) (Radke *et al*. 1978; Crutzen *et al*. 1979; Harden *et al*. 2000). Trace gases and aerosols have enormous consequences for regional air quality, pollution and climate (Crutzen and Andreae 1990; Langmann *et al*. 2009). In addition, trace gases produced during fire include a range of chemicals that are both non-toxic and harmful to humans including carbon dioxide, carbon monoxide, methane, ozone and volatile organic compounds (VOCs). The majority of the components of smoke are harmful to humans either during the fire (e.g. inhalation by firefighters) or in the smoke plume that has an effect away from the immediate fire area (e.g. reduced visibility, triggers for asthma).

The composition of smoke generated during fire mainly depends upon fire behaviour, which is controlled by interactions among fuel, weather and topography. Fuel and weather are also fundamental components of the combustion triangle (fuel, heat, and oxygen) as they influence the availability, density and moisture content of fuel and the supply of heat and oxygen during fire. Fuel moisture content (FMC) has an integral role in fire behaviour by determining rate of spread, fire intensity, fuel availability and fuel flammability (i.e. ignitability, combustibility, consumability and sustainability). The high specific heat capacity of water relative to other compounds means that water acts as a latent heat sink. Consequently, with increasing FMC more energy is required to drive moisture out of the fuel instead of being used to heat the material to initiate volatilisation and pyrolysis reactions. Therefore, with increasing FMC, flame temperatures are lower (Yang *et al*. 2004) as is heat yield or heat of combustion (Byram 1959).

This can lead to changes in combustion efficiency and the products of combustion (Lobert and Warnatz 1993).

A number of peer-reviewed studies have published emission factors (amounts of compound released per unit mass of fuel) for different fuel types and ecosystems. The majority of these studies have been undertaken in the United States or have been done in vegetation types not found in Australia, such as those found in the Mediterranean Basin. There is only a limited number of studies investigating fire emissions from vegetation in Australia, specifically, grasslands found in savannas (Hurst *et al*. 1994a; b; Paton-Walsh *et al*. 2010) and combustion of peat (Blake *et al*. 2009). Comparisons among these studies are difficult as the emission measurements are not all for the same range of gases (e.g. Shirai *et al*. 2003). Such limited data restricts our ability to model smoke composition during fire events and does not allow assessment of ecological and health consequences that may follow. Additional measurements of emission factors from new types of vegetation such as the *Eucalyptus* forests of south-eastern Australia are unknown but are vital for assessing the impact of biomass burning on air quality and climate. This project aimed to increase our knowledge of emissions as a result of fires in forests in south-eastern Australia and the underlying processes of flammability of types of fuel commonly found in these forests.

Research results

Four studies including one modelling exercise were planned during this project (Table 6). The three experiments were laboratory-based to allow for repeatable, highly controlled measurements. The research program was planned to firstly determine the role of one of the most important components of fire behaviour – fuel moisture content – on smoke emissions and fuel flammability (Experiment 1). Since the moisture content of live fuel held in the canopy of the overstorey and understory is dependent on plant water availability, the second step of investigation was designed to test if fuel from well-watered trees had similar smoke emissions and flammability characteristics as water-stressed trees (Experiment 2). To validate the results obtained in the first two experiments using trees grown under controlled condition, fuels from forested sites in southern Victoria were collected and combusted under similar conditions (Experiment 3). These data were used for modelling of greenhouse emissions using a range of different calculation methods (Experiment 4). An *ad hoc* study allowed the comparison of smoke composition and flammability of sub-tropical with temperate grasses (Experiment 5).

Some of the analytical equipment used in these experiments can be seen in Fig. 15. Briefly, combustion of material occurred in a ventilation controlled mass-loss calorimeter (MLC) to allow for quantification of heat release and mass-loss. Data related to the components of flammability, such as time-to-ignition, flame duration, mass-loss rate and residual mass fraction, could also be determined using this instrument. Smoke composition, in particular, CO_2, CO, and volatile organic compounds concentrations, were measured in air sub-sampled from the chimney stack of the MLC.

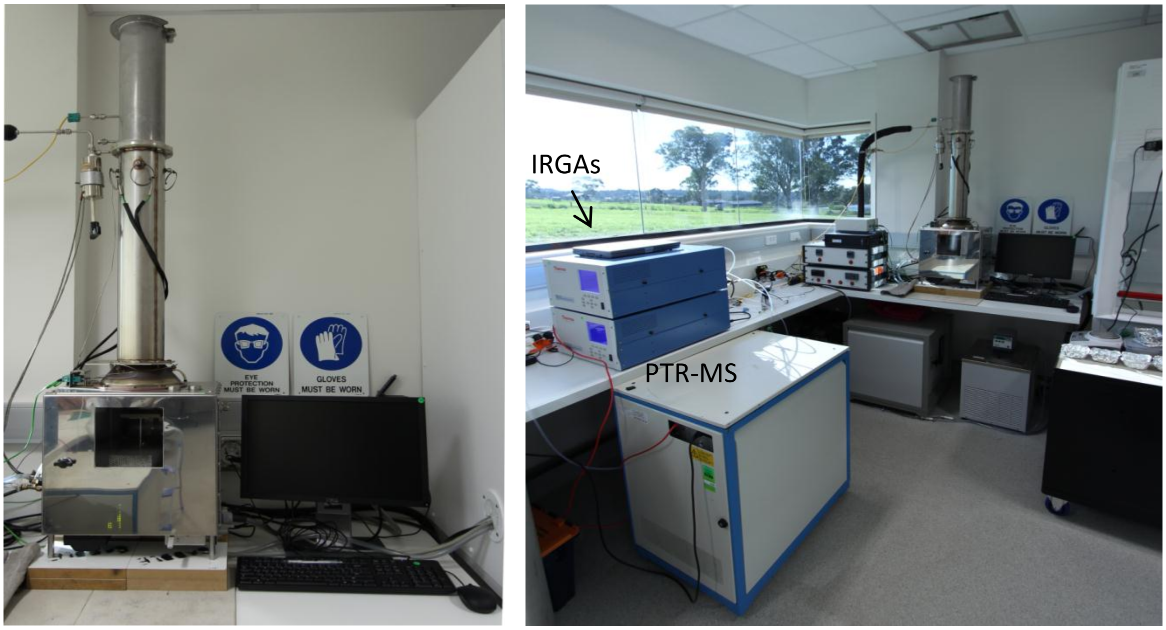


Figure 15. Equipment used in measuring gaseous emissions from combusting vegetation. In the left panel, plant material is combusted in a mass-loss calorimeter (MLC). The MLC measures energy release and mass loss from material combusted under a fixed irradiance. In the right panel, instrumentation to measure CO_2, CO (infra-red gas analysers; IRGAS) and volatile organic compounds (using a PTR-MS) can be seen.

Experiment 1 – Effect of fuel moisture content on greenhouse gas emissions
Leaves from three species of *Eucalyptus* were combusted in the mass-loss calorimeter to characterise the effect of fuel moisture on energy release and combustion products. The species selected were Sydney Blue Gum (*Eucalyptus saligna*), Southern Blue Gum (*E. bicostata*), and Forest Red Gum (*E. tereticornis*). Species in this genus are common in south-eastern Australian forests and woodlands; therefore the focus was to determine overall effects rather than to compare species. The data was then used to investigate whether relationships between leaf moisture content and the parameters measured can be described in a manner that can be used in fire behaviour or air quality models.

Findings showed that increasing moisture content reduced peak heat release and the effective heat of combustion (used in fireline intensity calculations) in a negative exponential pattern (Fig. 16a), while simultaneously increasing time-to-ignition. Estimates of the probability of ignition, based upon time-to-ignition data, indicated that the critical fuel moisture content for a 50% probability of ignition ranged from 81-89% on a dry-weight basis. As fuel moisture content increases, combustion efficiency reduces. This leads to an exponential increase to a maximum in CO emission factors across all three species (data not shown) relative to an exponential decline in the emission factors for CO_2 (Fig. 16b). VOC emission factors were found to change with increasing fuel moisture content in a manner similar to that of the CO emission factor.

Table 6. Timeline of research activities.

Activities	2010-2011	2011-2012	2012-2013	2013-2014
Testing of analytical equipment and development of sampling protocol				
Literature review				
Preparation and submission of manuscript (Smoke effect on plants)				
Data collection and analysis for effect of fuel moisture content experiment (Experiment 1)				
Data collection and analysis for effect of fuel moisture availability (Experiment 2)				
Data collection and analysis for field validation of greenhouse gas emissions (Experiment 3)				
Prepare and submit journal article for Experiment 1				
Final experimentation/data collection for modelling of greenhouse gas emissions (Experiment 4)				
Submit journal article for Experiment 2				
Data collection and analysis collection for comparative study of smoke emissions (Experiment 5)				
Prepare and submit journal article for Experiment 3				
Prepare and submit journal article for Experiment 4				
Prepare and submit journal article for Experiment 5				

This study showed that fuel moisture was found to have an effect on the release of energy, ignitability and the production of combustion products from the three *Eucalyptus* species. The results presented in this study show that any values of heat of combustion used to estimate fireline intensity should not remain fixed and must be varied according to fuel moisture content. In light of this, the extent to which fuel moisture content changes fireline intensity through modification of the fuel consumption component of the equation needs further investigation. The lack of significant differences among the responses of the three species supports the use of these data to identify general relationships among fuel moisture content and several related parameters that are used in fire behaviour or air quality models.

Experiment 2 – Effect of moisture availability on flammability and emissions

This study tested if plant water availability affected the fuel moisture content of live leaves, and therefore gaseous emissions in smoke. The same *Eucalyptus* species used in Experiment 1 were grown under three different watering regimes for 12 weeks to assess how different levels of water availability affects flammability and emissions.

At the time of harvest, all species had different soil moisture content but this difference was not reflected in the moisture content of leaves. Differences were measured in the flammability and emissions between fresh leaves and dried leaves (Fig. 17), which is consistent with the findings from Experiment 1, but no differences were identified between the watering regimes. This lack of sensitivity to water availability in *Eucalyptus* indicates strongly that leaf flammability and the formation of combustion products would be consistent over a range of climatic conditions. This hypothesis remains to be tested.

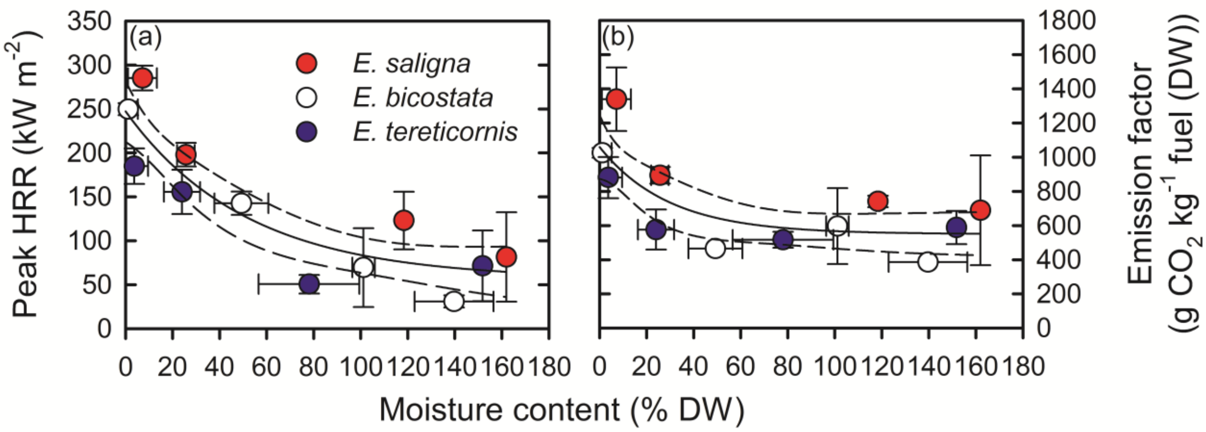


Figure 16. The effect of fuel moisture content on (a) peak heat release rate, and (b) emission factors for CO_2 for three *Eucalyptus* species (Possell and Bell 2013).

Once leaves are part of the leaf litter, their moisture content is a function of vapour pressure deficit, which itself is a function of the type of fuel, air temperature and humidity. Anecdotal evidence that vegetation in creeklines are not as flammable as surrounding vegetation and can act as fire breaks is therefore more likely due to the fuel moisture content of litter rather than living vegetation. Our results indicate that if forested landscapes have different water availability, there is likely to be little influence on flammability and emissions of leaf material before it becomes part of the ground fuel layer.

Experiment 3 – Field validation of greenhouse gas emissions and flammability

This experiment was designed to test that the results that we were seeing with trees grown under controlled conditions were representative of those from forests. This experiment also allowed us to examine the emissions from a wider range of fuel types and develop emission factors for gaseous compounds emitted by the combustion of these fuel fractions. Improvements in the certainty of emission estimates can come from either field or laboratory studies where burning conditions can be strictly controlled.

Canopy leaves, surface layer live fuels, leaf litter, duff and twigs (<6 mm) were collected from four lowland *Eucalyptus* forest sites situated near Orbost, East Gippsland. Fuel carbon content was measured before combustion in the MLC and also in the resulting ash. This allowed us to calculate how much of the original carbon in the combusted material is lost to the atmosphere. Measurements of CO_2, CO and volatile organic compound concentrations during the combustion of the different fuel fractions allowed us to calculate what proportion of the total carbon lost to the atmosphere is lost as these species. The average fuel carbon partitioning from the combustion of the *Eucalyptus* lowland forest fuel fractions can be seen in Fig. 18 and is compared to those from fires in the Sydney region (Hurst *et al*. 1996) and Australian savannas (Hurst *et al*. 1994).

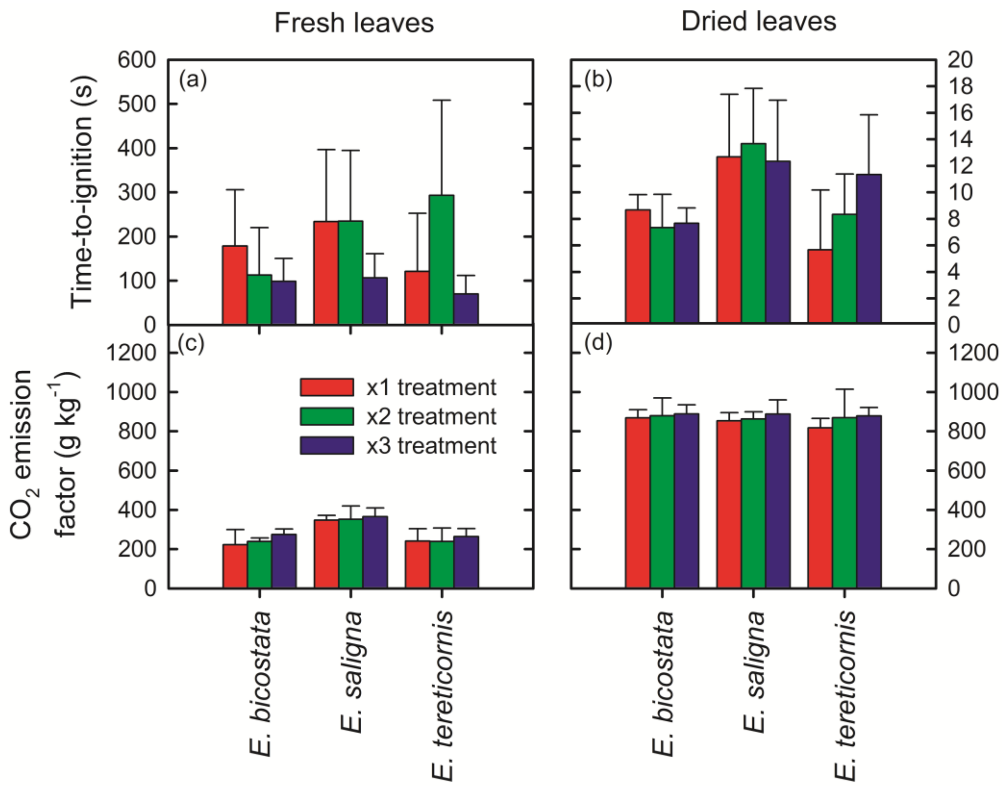


Figure 17. Effect of three different watering treatments on (a, b) time-to-ignition, and (c, d) CO_2 emission factors of fresh and dried leaves from the three different species of *Eucalyptus*.

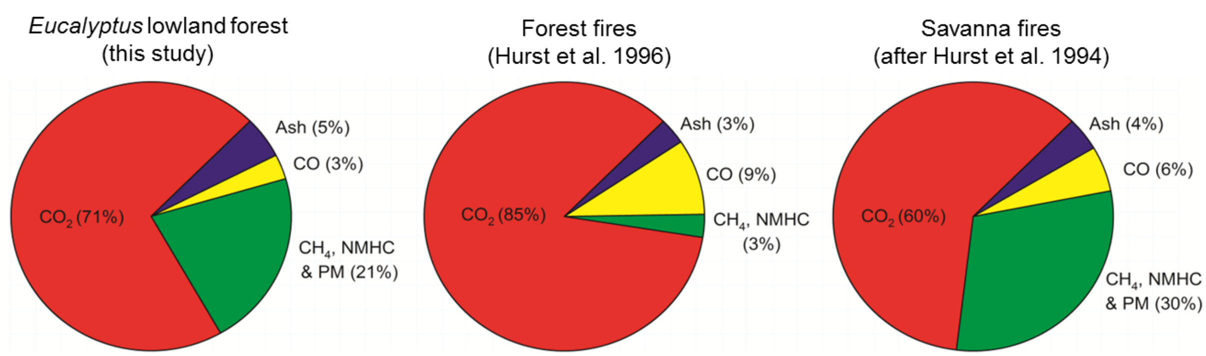


Figure 18. Fuel carbon partitioning in three different vegetation types. CO_2 = carbon dioxide, CO = carbon monoxide, CH_4 = methane, NMHC = non-methane hydrocarbons, PM = particulate matter carbon.

The overall amount of carbon lost to the atmosphere from prescribed burns in *Eucalyptus* lowland forests was similar to that found from forest fires in the Sydney region and those from Australian savannas. However, the partitioning of losses between the locations was found to be dissimilar. It should be noted that the study of Hurst *et al*. (1996) on forest fires in the Sydney region did not consider particulate emissions and that this may explain some of the discrepancy between the two locations.

Experiment 4 – Modelling of greenhouse gas emissions

Emissions from fire can be estimated if variables including the area burnt, the mass of fuel pyrolysed, the completeness of combustion, and emission factors for trace gases are known (Russell-Smith *et al*. 2009). The current methodology for calculating greenhouse gas emissions in Australia (AUS NIR 2011) uses default values of emissions factors for three vegetation types (forests, savanna grasslands and savanna woodlands), combustion completeness and fuel loadings for each state and territory. These are then used countrywide to estimate greenhouse gas emissions, in CO_2-equivalents, from fires. Measurements of fuel loading and carbon content of the various fuel fractions were made for the four sites used in Experiment 3 before and after hazard reduction burns. Using the emission factors calculated in Experiment 3, the total greenhouse gas emissions from the sites were calculated. These values were compared to estimates using default emission factors and combustion completeness values from the Australian National Inventory Report (AUS NIR 2011; Fig. 19).

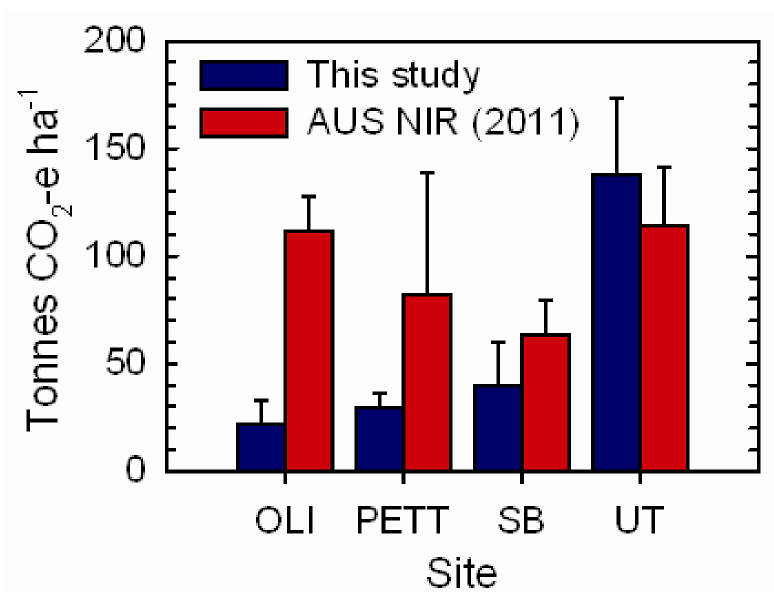


Figure 19. Fire emissions from four *Eucalyptus* lowland forest sites. Emissions were calculated using the methodology in the Australian National Inventory report (AUS NIR, 2011) with the data collected in this study and the AUS NIR (2011) default values. Site codes: Oli = Oliver Road, PETT = Pettmans Road, SB = South Boundary Road and UT = Upper Tambo Road.

The total fire emissions from the four *Eucalyptus* lowland forest sites were highly variable (Fig. 19). Calculations of total fire emissions using the default values from the Australian National Inventory Report over-predict emissions from three of the four study sites. These differences were caused by overestimation of the amount of biomass consumed in the Australian National Inventory default values.

Experiment 5 – A comparative study of smoke composition and flammability of sub-tropical and temperate grasses

Grassland occupies an area of approximately 440 million hectares in Australia and can be divided into two main regions: tropical/sub-tropical and temperate. Tropical and sub-tropical grassland covers large areas of northern Australia, extending from the Kimberley region in Western Australia, through much of the Northern Territory and into Queensland. Temperate grassland occupies a smaller north-south band across southern Queensland, New South Wales and Victoria between the arid interior and temperate forests along the east coast. Grass growth in recent years has increased due to heavy rains, influenced by the La Niña weather pattern following over a decade of drought. Consequently, there is value in knowing the composition of smoke that might be expected from fires in grassland and this extra experiment was added into the project.

Six grass species, comprising three species found in sub-tropical regions, and three species found in temperate regions were combusted in the MLC to determine their flammability and combustion products. All species were selected as they are the most common to each sampling site within each region. The sub-tropical grass species were Kangaroo Grass (*Themeda triandra*), Phalaris grasses (*Phalaris* sp.) and African Lovegrass (*Eragrostis curvula*). The tropical grass species were Feathertop Wire Grass (*Aristida latifolia*), Barley Mitchell Grass (*Astrebla pectinata*) and Mitchell Grass (*Astrebla* sp.).

Results showed a number of differences in the components of flammability and gas-phase emission factors between grass species. Except for CO_2, there were no obvious patterns between the two grasslands (Fig. 20a). Emission factors for CO_2 were greater for grasses collected in the sub-tropical grasslands (Fig. 20b). This is the first time such comparison has been made with Australian grasses.

Over the last three years of this project, the ability to control conditions in a laboratory environment has allowed for a rapid increase in data of emission factors from leaves of common *Eucalyptus* species in south-eastern Australia, different fuel fractions of a lowland *Eucalyptus* forest and a number of grass species found in Australia. We have shown that the proportion of carbon lost to the atmosphere because of fire in a lowland *Eucalyptus* forest is similar to other Australian vegetation types but the composition is different. We have demonstrated how different environmental factors, such as moisture content, affected flammability and smoke composition in a way that can be easily modelled. This project has improved our understanding of the relationships among fuel type and condition and burning conditions on emissions of gases.

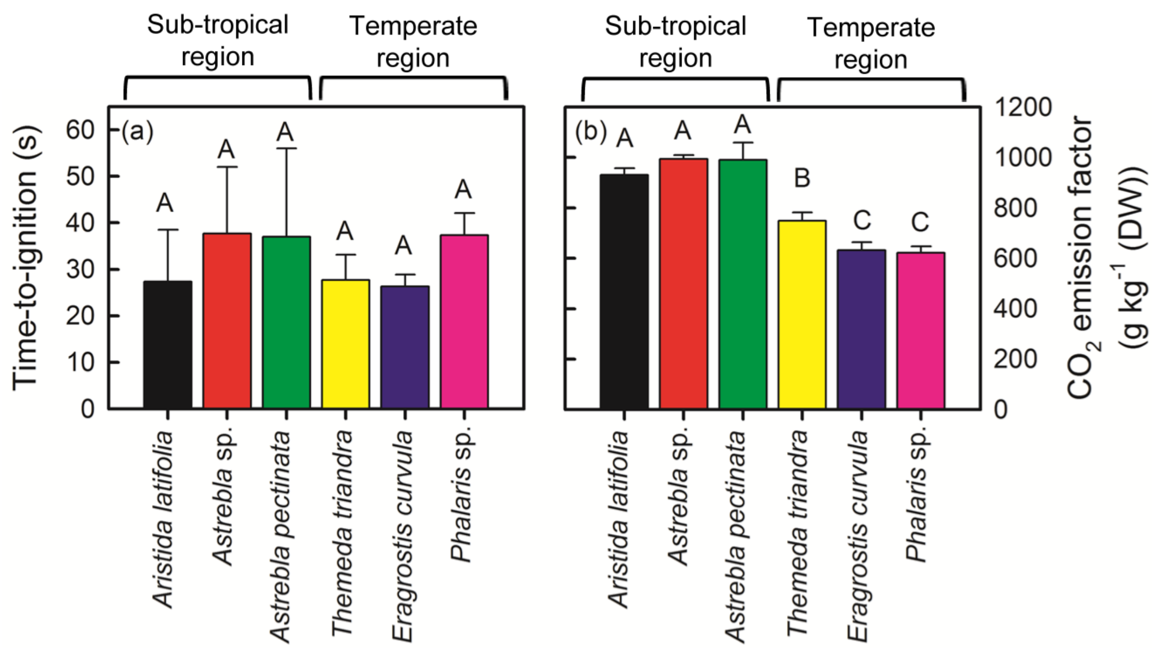


Figure 20. (a) Time-to-ignition and (b) emission factors for CO_2 measured during the combustion of the six grass species collected from tropical and sub-tropical regions.

Future research

It would be beneficial to know how FMC affects smoke composition under different heating intensities from both individual and mixed fuel components. With this knowledge, we could derive highly accurate emission factors that could be used in atmospheric emissions, dispersion and chemistry-transport models. Further beneficial investigations would quantify the influence of fuel moisture content and wind speed on smoke composition. This would enable us to partition emissions to different phases of combustion and calculate emission factors for smoke and plumes. Emission factors for many more vegetation and fuel types are needed but we have to take care that this information is collected in a rigorous and scientific manner (e.g. examining seasonal and spatial differences in grass fuels) and does not become a 'stamp collecting' exercise.

End User interaction

The research has been informed by the requirements of End Users through feedback given at Research Advisory Forums and annual Bushfire CRC conferences. For example, End Users requested additional samples on the effect of fuel moisture content on greenhouse gas emissions to include a wider range of fuel moisture content of the leaves tested. The study of smoke composition and flammability of sub-tropical and temperate grasses was instigated in response to the higher risk of grass fires from recent seasonal bushfire predictions. The temperate grass material for this experiment was collected by Adam Leavesley of ACT Parks and Conservation. ACT Parks and Conservation have also supplied fuels from other plant species for us to assess the smoke composition under prescribed burning conditions.

Through presentations of the research done in this project at regular Fire in the Landscape meetings, ACT Parks and Conservation have utilised the information on gas emissions and flammability and modified some of their work practices.

The uptake of this research by other End Users will be predominantly through the use of the emission factors, and how they are modified by fuel moisture, in smoke/air quality modelling, and greenhouse gas accounting. This will strengthen the accuracy of the calculations and be of great value to those developing and applying national carbon accounting models that include the effects of bushfires. For example, users of the carbon accounting model FullCam would be able to get a better overall picture of what is happening to their carbon stocks during and after hazard reduction burns. Emission factors for some of the plant materials burnt have been shared with CSIRO for use in their Bushfire CRC projects.

The experimental set-up used during this project allows for the rapid generation of large quantities of data. This data encompasses smoke composition, energy release and mass-loss and measurements associated with assessing flammability. Consequently, further collaboration with ACT Parks and Conservation is being planned to investigate how current land management practices could potentially affect flammability. Interest in being able to assess flammability of different fuel fractions has also been expressed by the Office of Environment and Heritage (NSW Government). Collaborations of this type allow for the concurrent determination of emission factors of gases, which then extends the number of emission factors available for Australia. Consequently, land managers increase the range and reliability of information available to them in terms of modelling fire behaviour and smoke composition during fire events, which can help assess the ecological and health impacts that may follow.

Outputs

Publications

Possell M, Bell TL (2012) The influence of whole plant water availability on combustion of *Eucalyptus* foliage. Bushfire CRC report, 21 p.

Possell M, Bell TL (2013) The influence of fuel moisture content on the combustion of *Eucalyptus* foliage. *International Journal of Wildland Fire* 22, 343-352.

Possell M, Bell TL (2014) A comparative study of smoke composition and flammability between Australian tropical and temperate grasses. *International Journal of Wildland Fire* (*in review*).

Possell M, Jenkins ME, Bell TL, Adams MA (2014) Emissions from prescribed fire in a temperate forest in south-east Australia: implications for carbon accounting. Biogeochemistry (*in review*).

Bell TL, Stephens SL, Moritz MA (2013) Short-term physiological effects of smoke on wine grapevine leaves. *International Journal of Wildland Fire* 22, 933-946.

Presentations

Bell TL, Possell M (2011) Greenhouse gas emissions and their environmental effects, NSW Fire and Rescue, Sydney.

Possell M, Bell TL (2012) Greenhouse gas emissions from fire and their environmental effects: a comparative study of smoke composition and flammability between tropical and temperate grasses. AFAC and Bushfire CRC Annual Conference, Perth.

Possell M, Bell TL (2013) Smoke emissions from lowland eucalypt forests: implications for carbon accounting. International Smoke Symposium, Maryland, US (October 2013)

Postgraduate student projects

1. The effect of smoke from bushfires and prescribed burning on plant physiology

PhD student: Vicky Aerts
Completed March 2014
Associated project: *Greenhouse gas emission from fire and their environmental effects*

Project summary

This study aims to determine the effect of smoke from bushfires and prescribed burns on the physiology of native and agricultural plants. With future predictions for climate change, bushfires in Australia are expected to increase and there will be a subsequently increase in the production of smoke. Recently, smoke from bushfires has become a major problem for the agricultural industry, especially for wineries that have suffered substantial financial losses due to smoke-tainted wine. Although a great deal of research has been done on the effects of smoke on seed germination, research about the effect of smoke on leaf gas exchange and its potential impact on agricultural crops is lacking. The research consists of four main projects:

1. *The effect of smoke on leaf gas exchange of a range of native and agricultural plant species*
   Leaf gas exchange measurements were made on 15 species of native and agricultural plants before and after exposure to smoke produced from combustion of *Eucalyptus saligna* leaf litter.

2. *Plant physiological responses to five different types of smoke*
   Four plant species were exposed to smoke produced from combustion of different fuel types: *Eucalyptus saligna* leaf litter, forest litter, *Pinus radiata* needles, a mixture of native and exotic grass species and wheat straw.

3. *Leaf anatomy and vulnerability to smoke*
   Leaf anatomical features were measured to determine morphological differences among species from native species fire-prone environments with agricultural species. Leaf characteristics such as surface area and thickness, moisture content, presence or absence of wax layers or hairs and cell distribution within leaves are being measured for comparisons.

4. *The effect of different smoke concentrations and exposure time on the leaf gas exchange*
   A smoke chamber was built to investigate the effects of different concentrations of smoke and exposure times. Light and ACi response curves were done using the Licor-6400 before and after controlled exposure to smoke. This data will be used to calculate biochemical parameters of C_3 photosynthesis models.

Presentations

Three poster presentations at the AFAC and Bushfire CRC Annual Conference (2011, 2012, 2013)

Two poster presentations at the Annual Research Conference for the Faculty of Agriculture and Environment, University of Sydney (2011, 2012)

Oral presentation to the Crop System Analysis Group at Wageningen University, Netherlands (September 2013)

Oral presentation to the Department of Environmental Sciences at the Faculty of Agriculture and Environment, University of Sydney (October 2013)

Oral presentation at the International Smoke Symposium in Maryland, US (October 2013)

2. Fire ecology of woody weeds in Australian forests and woodlands

PhD student: Felipe Aires

Completion scheduled for August 2014

Associated project: *Greenhouse gas emission from fire and their environmental effects*

Project summary

Effects of woody invaders on fuel load and structure, fire regimes and fire intensity remains poorly understood, particularly in Australia. A considerable but unknown number of alien plant species have been introduced to Australia. Differences in growth rate, plant architecture and ecophysiological characteristics among alien and native vegetation can alter fire regimes/behaviour and produce significant changes in the balance of carbon, nutrient levels and water cycle.

The first part of this research investigates the ecological effects of the highly invasive African Olive on fire behaviour. No studies have investigated the impact of this species on fuel structure and fire behaviour previously. This research aimed to determine the effect this invasion on the load and structure of fuels. A second study was conducted using the native, but invasive Cootamundra Wattle at Red Hill Nature Reserve in Canberra.

Fire intensity has become one of the standard gauges by which fire managers estimate the difficulty of controlling a fire and determine appropriate suppression action. The influence of invasive plants on fire behaviour, frequency and intensity may also vary according to the specific heat of combustion in each species. The third part of this research investigated the leaf traits and combustion features of invasive woody plants in forests of eastern Australia.

Measuring and modelling of fire behaviour began in the early 1930s and there is a continuum of approaches available today to measure and predict fires. The fourth part of this research aimed to use and compare different fire models to predict fire behaviour in invaded areas.

Presentations

Three poster presentations at the AFAC and Bushfire CRC Annual Conference (2011, 2012, 2013)

Two poster presentations at the Annual Research Conference for the Faculty of Agriculture and Environment, University of Sydney (2011, 2012)

Oral presentation at a special symposium on 'Invasive Species' at the 5th Joint Conference of New Zealand Ecological Society and Ecological Society of Australia, Auckland, New Zealand (November 2013)

3. Mechanisms underlying the patchy regeneration of woody legumes following bushfire

PhD student: Valerie Densmore
Completion scheduled for August 2014
Associated project: *Greenhouse gas emission from fire and their environmental effects*

Project summary

Woody legumes, such as *Acacia* spp. are found in almost every terrestrial ecosystem in Australia, and play a central role to restore ecosystems following bushfires. When their seeds are exposed to heat they germinate quickly, and many species often display rapid and widespread germination following moderate- to high-intensity bushfires. A low density population can fix up to 187 kg nitrogen per hectare in a year, and higher phosphatase concentrations are often found in the soil near their roots. Thus, woody legumes have been shown to boost net primary productivity, thereby increasing fuel production. However, densities of regenerating populations typically vary several orders of magnitude over small distances, producing patchy distributions that are currently unpredictable. Moreover, some ecosystems recruit woody legume species without fire.

The aim of this research was first to characterise soil properties and climate and geographic factors that significantly influence the densities of woody legumes following bushfire. Six representative species of woody legumes that germinated following the Black Saturday fires in Victoria in 2009 were identified growing at two to three densities. Ordinal logistic regression was used to analyse variables including physical and chemical characteristics of soil (0-10 cm depth) and geographic factors derived using ArcGIS and a one-second (30 m) digital elevation model. The best predictive model selected using discriminate analysis indicated factors that influence availability of phosphorus.

On the basis of this finding, fine roots were collected from field species and also following a glasshouse study varying phosphorus concentrations. Molecular techniques were used to investigate whether these woody legume species possessed and expressed genes to increase available phosphorus.

In a third line of enquiry, optimal temperatures required to germinate species from different climate zones were compared to elucidate if moderate to high-intensity fire are the sole trigger for their germination *en masse*. Arid-zone species were found to germinate optimally at temperatures reminiscent of solar radiation, rather than fire.

Overall, this study helps reveal mechanisms underlying distributions of woody legumes following bushfire or other disturbances. The ability of woody legume species to promote higher productivity in ecosystems makes them an important contributor to fuel loading, thus understanding what prompts high density populations of woody legumes may support land management decisions, particularly concerning hazard-reduction burns.

Presentations

Three poster presentations at the AFAC and Bushfire CRC Annual Conference (2011, 2012, 2013)

Two poster presentations at the Annual Research Conference for the Faculty of Agriculture and Environment, University of Sydney (2011, 2012)

Oral presentation at the Fire in the Landscape meeting, Sydney (March 2013)

Oral presentation at the Association for Fire Ecology Conference, Portland, US (December 2012)

Oral presentation at the 5th Joint Conference of New Zealand Ecological Society and Ecological Society of Australia, Auckland, New Zealand (November 2013)

4. What are the impacts of wildfire on the hydrology of Sydney's water supply catchments?

PhD student: Jessica Heath

Completed August 2013

Associated project: *Fires and hydrology of south-eastern Australian mixed-species forests*

Project summary

Bushfires modify the hydrology of a sub-catchment and ultimately affects water flow at its outlet. Loss of vegetation and litter decreases in decomposed organic matter and change in soil properties (e.g. formation of water-repellent soils) cause a decrease in infiltration rates and an increase in runoff. It has been suggested that if vegetation and litter cover are reduced to 10%, overland flow can increase by more than 70% leading to higher water yields immediately post-wildfire.

Studying hydrological responses to wildfire can be difficult and complex. In Australia there are few examples of paired pre- and post-wildfire hydrological data owing to our heterogeneous topography and vegetation, variation in wildfire severity and wildfire history. Most hydrological studies have examined patterns in peak streamflow discharge post-wildfire. However, a limited number of studies have demonstrated water yield in forested sub-catchments can be significantly reduced after severe wildfire. Australian examples are predominately limited to the Ash forests of Victoria, primarily relating regeneration of *Eucalyptus regnans* (Mountain Ash) forests to water yield. Langford (1976) demonstrated that water yields in burnt *E. regnans* forests declined significantly after a period of 3-5 years owing to a proliferation of seedlings. Findings of these studies cannot be directly extrapolated to predict the impact of wildfire on forested catchments of NSW as the physiology of *E. regnans* is quite unique and unlike that of any eucalypt of NSW.

The aims of this research were to:

1. Determine the impacts of severe bushfires on post-wildfire hydrology

2. Compare the responses of selected catchments to other studies within Australia and globally
3. Compare physical-based and statistical methods for identifying the impact of fire on hydrology

This project examined the impact of the 2001/2002 bushfires in the outer Sydney Basin on the hydrology of nearby forests and forested catchments. The Sydney Catchment Authority monitored the response of vegetation and soil to these fires. This project expanded this dataset by examining the effect of bushfires on water supply and quality and explored how the hydrology of the catchments recovered towards pre-wildfire conditions. The outcomes of this research will provide government bodies that manage public land (e.g. Department of Industry and Innovation and Sydney Catchment Authority) with a more comprehensive understanding of how bushfires impact the hydrology of forests and catchments.

5. Effects of fire on carbon fractions in forest soils

PhD student: Hari Shrestha
Completion scheduled for August 2014
Associated project: *Environmental impacts of prescribed and wildfire – emissions management*

Project summary
Low intensity prescribed (planned) fire is being used increasingly to reduce the risk of wildfire in south-eastern Australia. However, our present knowledge of ecological impacts of repeated prescribed fire on soil carbon and available nutrients is relatively poor and needs to be improved for sustainable management of native forests. This study aims to investigate the effects of repeated low intensity prescribed fire on the formation and distribution of soil organic matter (SOM) fractions (e.g. particulate, humic and char-C). The availability of soil nutrients such as nitrogen and phosphorus can be affected by changes in the composition of SOM due to long-term burning and this will also be investigated. The study will improve our knowledge about the fire effects on soil C dynamics in Australian forest ecosystems and the results will contribute to the scientific basis underpinning planned burning in sustainably managing Australian native forests.

The field study sites were located at five Fire Effects Study Areas in the Wombat State Forest, north-west of Melbourne. Low intensity fire treatments have been applied since 1985 in spring and autumn at 3 year (S3 and A3) and 10 year (S10 and A10) intervals to previously long unburnt forest. Litter and soil were sampled in 2012 after 26 years of burning treatments.

Work completed to date includes field sampling and sample processing; determination of volumetric mass of soil and litter, soil moisture content, particle size analysis, soil organic matter fractionation (wet sieving) and soil bulk density; chemical analysis Total C and N and organic matter content (loss-on-ignition); mid-infrared spectroscopy (spectra collection and analysis using MATLAB and PLS tool box. Other techniques employed have been char-C analysis by acid digestion (hydrogen peroxide and nitric acid), measurement of potential mineralisable N by hot KCl extraction and soil respiration using a Respicond.

Presentations

Two poster presentations at the AFAC and Bushfire CRC Annual Conference (2012, 2013)

Two oral presentations at the Annual Student Research Symposium for the Department of Forest and Ecosystem Science, University of Melbourne (2012, 2013)

Poster presentation at the Joint SSA and NZSSS Soil Science Conference, Hobart (2012)

Poster presentation at the North American Forest Soil Conference, Whitefish, Montana, United States (2013)

6. Predicting and understanding post-wildfire hydrogeomorphic sensitivity of landscapes

PhD student: Rene van der Sant

Completion scheduled for December 2014

Associated project: *Quantifying risk of water quality impacts from burned areas*

Project summary

The aim of this study is to assist prediction and understanding of sensitive post-fire responses in south-eastern Australian forests. To achieve this aim, spatial predictor variables will be related to observed post-fire erosion response, soil properties and hydrologic processes. In particular, an aridity index will be linked with observed debris flow response after wildfires in 2009. Aridity will also be shown to be correlated with soil properties important for hydrological response, particularly stable macroporosity. As runoff during intense storms is known to effect debris flows, runoff response of burnt soil will be investigated at a recent wildfire across an aridity gradient. Results will have important implications for fire and resource management, as well as increasing scientific knowledge. The research consists of four main projects:

1. *Remotely sensed catchment response: channel initiation*
   GIS and aerial photography was used to empirically assess the relationship between channel movement and remotely sensed predictor variables. A method to determine the location of channel initiation has been developed and error associated with the method has been quantified. A Python script extracts information from each spatial data set about each catchment.

2. *Remotely sensed catchment response: debris flow*
   This project uses GIS and aerial photography to empirically assesses the relationship between debris flow occurrence (a binary-dependent variable) and remotely sensed predictor variables (e.g. properties of a landscape, fire and rainfall). A method to identify debris flow producing channels/catchments has been developed and verified.

3. *Linking soil properties and response*
   This project proposes that aridity is related to soil properties, particularly stable macroporosity. A field study to measure soil properties which assist in macropore stability and infiltration will be done across an aridity gradient.

4. *Linking system processes and response*
   The hydrological response to rainfall is measured in soils from burnt areas across an aridity gradient to confirm the soil properties match with observed processes. Tipping buckets and data loggers were used to record real-time overland flow during winter and spring storms.

Presentations

Van der Sant R, Sheridan G, Rijkee P, Nyman P, Lane P (2013) The hydro-geomorphic sensitivity of forested water catchments to wildfire. In: Proceedings of the AFAC and Bushfire CRC Conference Science Day, RP Thornton, LJ Wright (Eds.), Perth.

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