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Welcome from Editor

It is my pleasure to bring to you the compiled papers from the Science Day of the AFAC and Bushfire CRC Annual Conference, held in the Sydney Convention Centre on the 1st of September 2011.

These papers were anonymously referred. I would like to express my gratitude to all the referees who agreed to take on this task diligently. I would also like to extend my gratitude to all those involved in the organising, and conducting of the Science Day.

The range of papers spans many different disciplines, and really reflects the breadth of the work being undertaken, The Science Day ran four steams covering Fire behaviour and weather; Operations; Land Management and Social Science. Not all papers presented are included in these proceedings as some authors opted to not supply full papers.

The full presentations from the Science Day and the posters from the Bushfire CRC are available on the Bushfire CRC website www.bushfirecrc.com.

Richard Thornton

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Erosion and risk to water resources in the context of fire and rainfall regimes

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Abstract

The potential impacts of post-fire erosion on water quality are well documented in the literature. To date, research in this area has focused primarily on post-fire erosion processes and water quality impacts in the context of fire severity and vulnerability of hydrological systems to fire impacts. Accordingly, model development has been driven by the need to predict post-fire erosion given the burn impact and different rainfall conditions. However, there are no tools available for land managers to predict frequency and magnitude of erosion events under variable fire and rainfall regimes. Over time, the fire regime represents an important variable that can lead to changes in risk, especially given the strong influence of anthropogenic activities and climate change on fire regimes. Across landscapes, the regional variability in both fire and rainfall regimes may result in different levels of risk depending on the likelihood of storms intersecting with burnt areas. Fire and storms represent stochastic processes in space and time, in contrast to the deterministic nature of geophysical post-fire erosion processes. In this paper we propose a new risk framework which incorporates regional fire and rainfall regimes as stochastic variables in a system where erosion processes and sensitivity to fire effects represent landscape vulnerability, which is site-specific and driven by deterministic processes.

Introduction

Forest and rangeland fires (both prescribed fire and wildfire) impact on a wide range of social, economic and environmental values and land managers face a complex task in balancing the costs and benefits of different approaches to fire management. Management strategies must consider both the first-order effect of fire (injury, loss of life, property and livestock and damage to infrastructure) and second order-effects such as air pollution, erosion and water quality impacts, post-fire hydrological hazards, and altered ecosystems. This presents a very complex decision making environment with short- and long-term considerations across a large number of stakeholders and agencies with ‘different goals and mandates’ (Rieman *et al.* 2003; Wilson *et al.* 2011). Furthermore, risk factors often operate at multiple spatiotemporal scales and are subject to uncertainties stemming from both natural variability (stochasticity) and incomplete understanding of the processes and components that constitute the overall risk (Thompson and Calkin 2011).

The risk associated with erosion and flash flooding from burnt landscapes represents a second-order impact of fire. The potential impacts from post-fire erosion on water quality, infrastructure and human life are well documented in the literature (eg. Emelko *et al.* 2011; Rieman *et al.* 2003; Smith *et al.* 2011). Both statistical and physical-based approaches have been used in predicting the erosion response of burned catchments in different contexts, e.g. water quality (Benavides-Solorio and MacDonald 2005; Larsen and MacDonald 2007; Robichaud *et al.* 2007) hydrological hazards (Cannon *et al.* 2010) and geomorphic processes (Moody *et al.* 2008b). However, there are currently no predictive tools available to land and fire managers to determine how erosion and the associated risk responds *over time* to landscape-scale fuel management strategies, changing fire regimes and changing weather patterns.

What is the effect of annual prescribed burning rates on the likelihood of large erosion events occurring across the landscape? What is the effect of regional variation in rainfall regimes on the likelihood of post-fire erosion impacting water quality? How will the frequency and magnitude of erosion events be affected by climate- induced changes to fire regimes?

These are questions that typically face land managers during strategic planning and policy development where both short and long term outcomes are considered across multiple values and stakeholders. It represents a different level of inquiry to the currently available post-fire erosion models (e.g. Robichaud *et al.* 2007) and post-fire assessments of hydrological risk (e.g. Sheridan *et al.* 2009).

In this paper we review the current state of knowledge in terms of predicting post-fire erosion. We then present a conceptual risk model which highlights the different role of landscape controls, fire regimes and rainfall as components of the overall risk picture. Finally we conclude with suggestions for a new modelling framework which incorporates fire and rainfall regimes as variables which influence the erosion hazard and the overall risk to water resources.

Fire in the landscape and water quality - what’s the problem?

As major disturbance events in forested landscapes, wildfires can have a large impact on hydrological processes and landscape vulnerability to erosion (Swanson 1981). Increased erosion and sediment export from burnt catchments has been documented in major fire prone regions of the world including southeast Australia, the western USA, South Africa and the Mediterranean (e.g. Lane *et al.* 2006; Moody and Martin 2009a; Scott 1993). Process based research on runoff and erosion processes and fire effect on soil properties show that this increase in erosion is primarily due to:

i. Increased surface runoff and peak flows (increased transport capacity) due to removal of vegetation, reduced hydraulic roughness, and the reduced infiltration rates of burnt soils (Cerda and Doerr 2005; Imeson *et al.* 1992; Martin and Moody 2001; Sheridan *et al.* 2007)
ii. Reduced resistance to erosion (increased sediment supply) due to addition of vegetative ash, removal of vegetation, and reduced soil cohesion due to heat impacts from the burning (Moody *et al.* 2005; Robichaud *et al.* 2010; Sheridan *et al.* 2007)

To date, research has mainly focused on how hydrological systems respond to fire; the impacts of fire on soil physical properties; the underlying runoff and erosion processes; and catchment scale geomorphic and hydrologic responses. Shakesby and Doerr (2006) provide a comprehensive review on fire as a hydrological and geomorphic agent, with several other reviews available for more site specific conditions (Ice *et al.* 2004; Neary *et al.* 2003; Shakesby 2011; Shakesby *et al.* 2007; Wondzell and King 2003). Figure 1 provides a broad overview of the trends in recent publications related to fire and erosion.

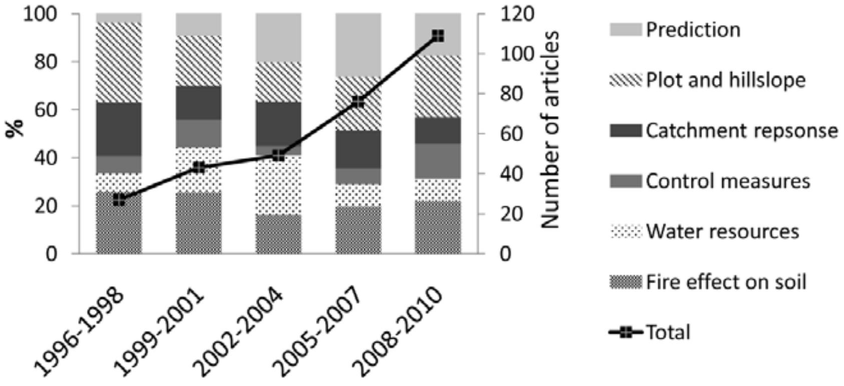

Figure 1. The figure is based on more than 400 results returned by ISI Web of Science using four search terms: ‘fire and erosion’, ‘fire and runoff’, ‘fire and water quality’ and ‘fire and infiltration’.

Post-fire impacts on water quality occur mainly through the transfer of particulate and dissolved constituents from burnt hillslopes and ephemeral channels to permanent water bodies. Impacts have been documented in the form of increased turbidity, increased levels of nutrients (N,P), trace elements (Fe, Mn, As, Cr, Al, Ba & Pb) and solutes (Na^+, Cl^-, and SO_4^{2-}) (Smith *et al.* 2011). While the transfer of pollutants can occur through both surface and subsurface processes, the impact occurs largely through pulses of sediment and other pollutants from surface runoff and erosion during high intensity rainfall events in susceptible upland catchments (Bisson *et al.* 2003; Lane *et al.* 2006; Miller *et al.* 2003; Moody *et al.*

2008a; Nyman *et al.* 2011). The burned landscape is characterised by stores of available sediment with different residence times that are determined by the net flux of sediment between them (Figure 2). Transfer processes can be either purely gravity driven (dry ravel), surface hydrology driven (rill and channel erosion, runoff generated debris flows) or subsurface hydrology driven (mass wasting). Here we are concerned with transfer processes that are driven by surface hydrological processes.

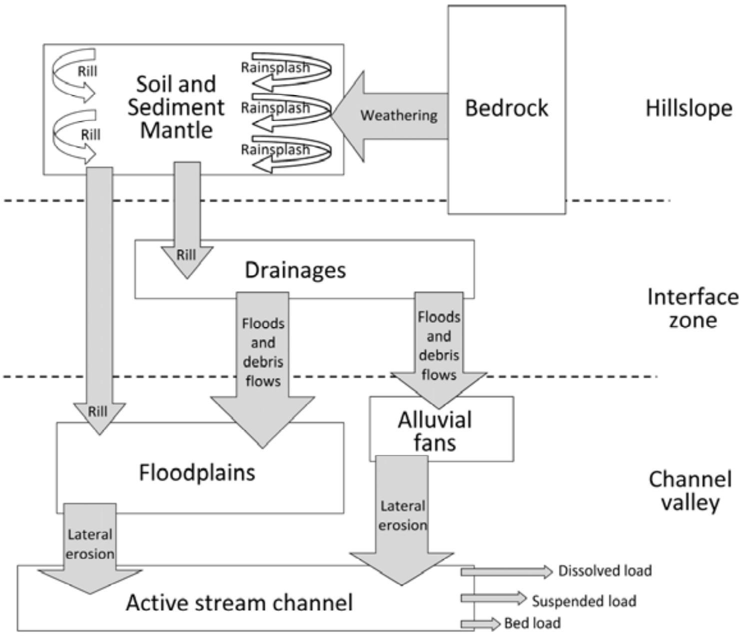

Figure 2. Components of a burned landscape. Sediment storage reservoirs are shown as rectangles and the transfer processes as gray arrows. The areas of the rectangles are roughly proportional to the residence times and the widths of the gray arrows are roughly proportional to the flux of sediment between storage reservoirs. The interface zone is the area between the channels and the hillslope, which can be described as unchannelised drainages (from Moody and Martin 2009b).

The intersection between rainfall events, burned areas and susceptible catchments occur episodically in patches and can therefore often be viewed as discrete events in space and time, in a similar manner to landslides (Istanbulluoglu *et al.* 2004; Nyman *et al.* 2011). These discrete events inject sediment and other potential pollutants into active stream channels where they are gradually transported downstream. While discrete post-fire erosion events in upland catchments may provide the main source of constituents, there are large spatial and temporal uncertainties associated with the transfer of sediment and other pollutants from source to a defined asset or point of impact (Gomi *et al.* 2002). In uplands catchments sediment transfer is driven by surface hydrological processes. At larger scales the sediment transfer is linked to geomorphic and hydrologic processes such as subsurface flow, flow routing and floodplain structure (Benda and Dunne 1997; Gomi *et al.* 2002; Lancaster and Casebeer 2007). In many cases, these processes can be considered to operate more or less independently of the fire disturbance This means that fire impacts on erosion are most pronounced at small scales where surface processes dominate and that the initial perturbation to water quality at any scale within a system is primarily linked to the supply of constituents from source areas in upland catchment. The majority of post-fire erosion research is therefore conducted at hillslope and small catchment scales.

How can risk be quantified in order to meet the demands of land managers?

Risk perspectives vary depending on management context and the spatial temporal scale at which risk is being assessed. In hydrology and geomorphology, the focus is on characterising and predicting hydrological events and the geophysical processes that drive the frequency and magnitude of post-fire erosion. The main task is not to quantify risk *per se*, but rather to provide the predictive tools required as inputs to risk assessment conducted by land and water management agencies. In a risk framework these predictive tools provide a measure of hazard. In a water supply system for instance, the hazard is the predicted frequency, magnitude and duration of post-fire water quality impact. These predictions in turn provide an input for quantifying the overall risk in the context of water quality thresholds, reservoir treatment capacity, alternative supply sources, etc. Here, the geophysical processes that lead to erosion events and that underlie the hazard are in themselves less relevant. The same principle applies to aquatic ecosystems where the risk is a function of ecosystem vulnerability and resilience given the hazard (predictions of post-fire water quality impacts). In this paper we refer to hazard as the frequency and magnitude if erosion events. The risk is the effect of erosion events on assets and is therefore a function of the hazard and the vulnerability.

The level at which the hazard is quantified must reflect the dominant processes that operate at the spatial or temporal scale at which events and management activities are defined. From an *operational* perspective for instance, management activities can influence risk through erosion mitigation works, the timing of prescribed fire and the pattern of prescribed burn in relation to drainages. The burn pattern applied during prescribed fire operations might influence the connectivity between hillslopes and drainages. At this scale of assessment, the hazard is a function of the hydrological connectivity and erosion processes occurring on hillslopes after fire. Here, models and hydrological research can address questions relating to the effectiveness of erosion control works (e.g. Robichaud *et al.* 2007) or the effect of burning patterns on connectivity between streams and drainages (e.g. Moody *et al.* 2008b) . At a *strategic* management level on the other hand, the risk is influenced by climate change, regional weather patterns, resources allocated towards fire suppression, annual prescribed fire targets, strategic fuel reduction burns and other regional fire management strategies. Here hydrologists can address questions relating to the change in hazard as a result of, for instance, increased wildfire occurrence or other changes to fire and rainfall regime parameters (e.g. Istanbulluoglu *et al.* 2004). In this case, predictions should be targeted toward detecting the change in the frequency and magnitude of erosion events (hazard) due to changing fire regimes and changing weather patterns.

A complete risk picture requires a risk analysis which involves i) identifying hazards or water resources at risk, ii) quantifying the degree of impact according to the frequency, extent and severity of fire, and iii) estimating the consequence for a range of potential impacts. The bow and tie diagram in Figure 3 is a simplified risk picture which links fire and rainfall regimes to the potential consequences to a water supply system due to post fire sediment delivery to the reservoir. The horizontal bars represent causes and consequence, vertical bars represents controls such as landscape vulnerability, treatment capacity or post-fire mitigation activities. The hazard is the measure of the potential impact given burn areas, rainfall, and landscape vulnerability and rehabilitation efforts. Quantifying the total risk to water supply is clearly a complicated task requiring information on i) the natural fire and rainfall regimes , ii) the susceptibility of landscapes to post-fire erosion, iii) spatiotemporal transfer processes and iv) the vulnerability of various assets to water quality impacts. Climate change, fire management and erosion mitigation strategies further complicate the risk picture.

Fire and erosion as geophysical processes are associated with large statistical uncertainties (stemming from natural variability and stochastic processes) and epistemic uncertainties (stemming from the lack of perfect knowledge) (Aven 2008; Helton *et al.* 2004). Statistical uncertainties are brought to the system through the random, spatial and temporal variability that is typically associated with climate and biophysical systems such as fire regimes and rainfall. These uncertainties reflect reality and can be incorporated into a modelling environment without loss of predictive power. Epistemic uncertainties however are more problematic in that they stem from the incomplete understanding and lack of data on how fire and rainfall processes translate into an undesirable outcome (i.e. water quality impact). In Figure 3, epistemic uncertainties are found across the entire risk picture, in the causes (fire and rainfall regimes), the vulnerability (landscape controls and transfer processes), rehabilitation (effectiveness) and water quality thresholds.

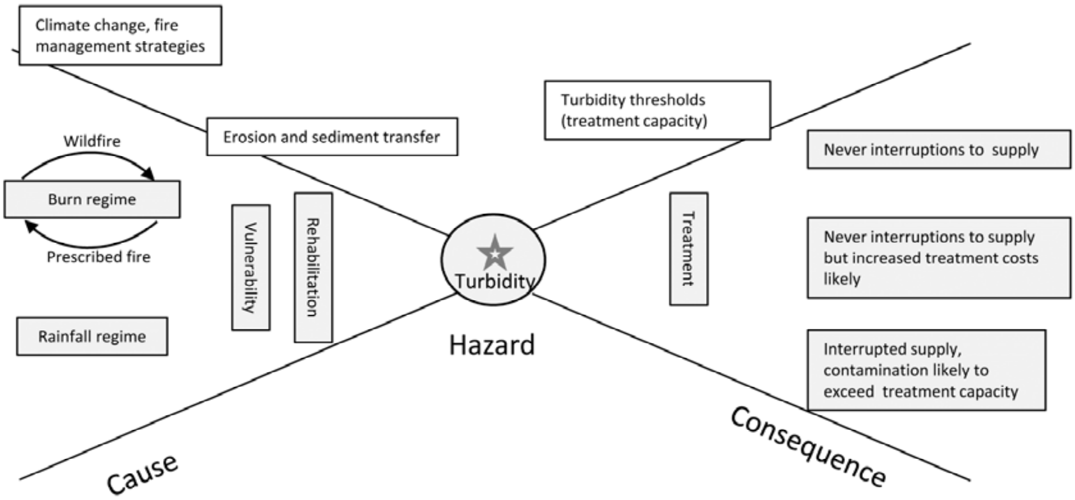

Figure 3. Bow and tie diagram outlining the risk picture for water supply catchments where the hazard is defined as the delivery of sediment to the reservoir. The horizontal bars represent causes and consequence, vertical bars represents controls such as the landscape vulnerability, treatment capacity or post-fire mitigation activities. Here the hazard is equal to the impact turbidity as indicated by the star.

Large epistemic uncertainties can obscure the signal from real effects in a model. In Figure 3 for instance, the hazard is equal to the impact and defined as the frequency and magnitude of sediment delivery event to the reservoir. Under this scenario, *what is the impact of* *changing fire regime on the hazard?* The large uncertainty associated with the controls (landscape vulnerability and rehabilitation) means that it is difficult to detect the effect of a changing fire regime on the hazard as it is defined here. The model would need to estimate the sediment delivery from the range of all possible (random) combinations of fire and rainfall events, an exercise requiring large number of parameters (=uncertainties) and modelling steps (=more uncertainties).

An alternative would be to view the hazard as the rate of intersection between rainfall events (storms) and burned areas (Figure 4). Here, the hazard translates into a consequence via landscape vulnerability, rehabilitation and treatment capacity. This means that a flat terrain with frequent fire and storms (e.g. savannah) can have a high hazard score but a very small likelihood of impact given the low vulnerability. The effect of fire regimes on the hazard is more likely to be detected in this conceptual risk model, given the reduced sources of uncertainty. If the landscape controls and hydrological transfer process are stationary, then any change in hazard would be proportional to the change in overall risk. With this definition, the risk model is more effective at quantifying changes in risk given variable climate, changing fire regimes and strategic fire management. However, if the interest is precise predictions of contamination following a wildfire or prescribed fire, then the hazard is better defined by some measure directly linked to hydrologic connectivity and sediment delivery to the reservoir (e.g. Figure 3).

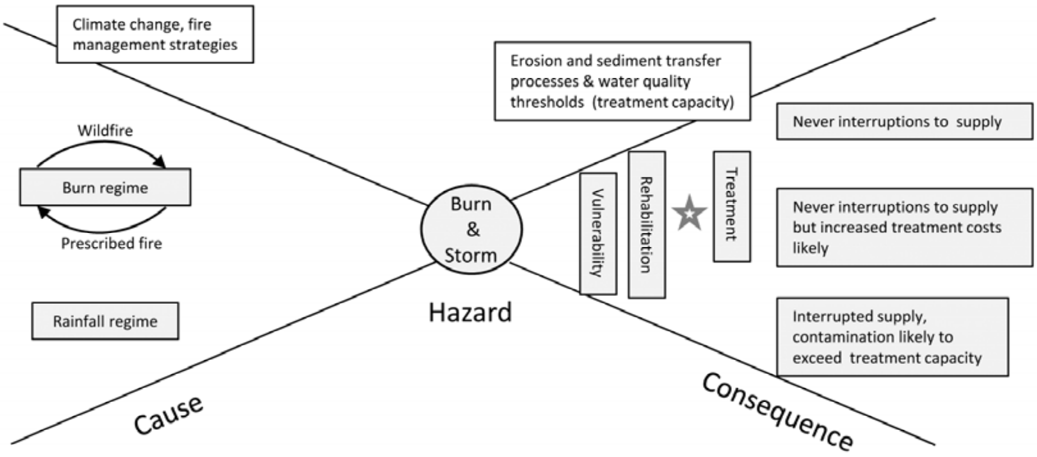

Figure 4. Bow and tie diagram outlining the risk picture for water supply catchments where the hazard is defined as the intersection of storms and burn areas within the catchment. Here the turbidity impact (star) occurs as a result of the hazard and the vulnerability.

Summary and future directions

The vulnerability of ecosystems and water supply systems to the impacts of post-fire erosion is often a function of critical thresholds. This means that the majority of the hazard is embedded in a relatively small number of high magnitude events that exceed critical thresholds. When contamination exceeds thresholds, the consequence is a function of the ability of the system to cope. In a water supply reservoir, the ability to of the system to cope is dependent on infrastructure such as treatment capacity, flexibility in off-take depth as well as alternative water supply sources. In aquatic ecosystems, the ability to cope is related to resilience or ability to bounce back from the disturbance

Common to all systems at risk from post-fire erosion is that the root cause of the hazard is linked to the intersecting burn (B) and rainfall (R) regimes (B∩R). Vulnerability (V) and post-fire rehabilitation (R) influence the way in which the cause translates to geomorphic/hydrological impact. The actual risk is in the end determined by the water quality thresholds (T) associated with the asset. Hence,

$$\text{Risk} = (B \cap R) * V * R * T$$

The hazard can be given different definitions depending on the level at which risk is being assessed. When the risk is assessed as function of erosion and sediment transfer processes *following* fire (connectivity, erodibility, burn patterns, etc...) then the hazard includes (B∩R, V and R. This is often the case in post-fire situations when priorities and management strategies are set based on the variability in erosion potential (hazard) across a burnt area. On the other hand, if risk is quantified *over time* as a function of climate change, burn regimes and rainfall regimes, then the hazard is better defined by fire and rainfall regimes (B∩R) alone. For instance, the difference in risk within a catchment due to different fire and rainfall regimes is independent of the landscape properties (V) or post-fire rehabilitation (R). This means that when the hazard is defined as B∩R, it is independent of site specific hydrological and geomorphic properties and processes. Excluding post-fire geophysical processes from the hazard term in turn means that the causes (rainfall and fire) can be linked to hazard with a higher degree of certainty.

The tendency is for research to focus on quantifying erosion and water quality impacts within burn areas following fire. Few attempts have been made to model post-fire erosion in the context of the causes - rainfall and fire. We propose that the aim should also be for research to characterise fire (the perturbation) and rainfall (the driver) as interacting spatial and temporal processes (e.g. Jones *et al.* submitted). This would allow for more robust analysis of the effects of prescribed fire and climate change on the risk to water resources. Both rainfall and fire represent complex landscape processes which vary across landscapes and over time.

In order to model these interactions more work is needed on questions relating to the effect of prescribed burning and climate change on the susceptibility of the landscape to post-fire erosion events. Prescribed fire means that perturbations appear more frequently in the landscape; however, they result in a reduction in extent and severity of wildfires. Modelling efforts should aim to incorporate the linkage between wildfire and prescribed fire and show how the risk to water resources responds to fire regimes given different fire management strategies. Fires represent hydrological perturbations which appear in the landscape and diminish as recovery progresses. As disturbance events prescribed fire and wildfire need to be treated differently both in terms of their hydrological impact and the way in which they appear in the landscape. Prescribed fire regimes are dominated by frequent, less extensive low severity fires compared as opposed to the less frequent, more extensive high severity wildfires. When applied across a landscape these different regimes result in variable rainfall thresholds for the initiation of high magnitude erosion events. As such, the different component of the fire regimes can be modelled as separate hydrological systems with different hydrological response potential. The concept of leverage or prescribed burn efficacy may can link the deterministic application of prescribed fire in the landscape to the extent and severity of (a stochastic process) (Bradstock and Williams 2009). The modelling approach aims to represent prescribed fire and wildfire as separate hydrological perturbations with different magnitudes. The aim is to address question relating to how the overall landscape is likely to respond under different climate change and fire management scenarios, when prescribed fire and wildfires are modelled simultaneously but as separate components of the overall fire regime. This approach is dependent on reliable data and simulated outputs from fire regime studies.

Another important avenue for future research would be to capture and quantify the landscape-scale variability in the sensitivity to the impacts of fire. This is a necessary step for linking a fire perturbation to erosion response potential. The effect of fire on hydrological processes depends on both the pre-fire vulnerability of the landscape to erosion and the sensitivity of the hydrological system to fire impacts. Fire regimes should be defined within eco-region (or functional response units) where fire effects can be directly linked to hydrological perturbations using a measure of sensitivity to fire impacts. Fire impacts and landscape susceptibility can then be combined to represent vulnerability.

Finally, we need more information on the frequency and magnitude of rainfall events that drive post-fire erosion events. A spatial temporal representation of rainfall requires information on the frequency of events, the intensity and duration of events and their spatial distribution. Both the measurement and modelling of these rainfall properties is a challenge. However, recent improvements in spatial information on rainfall (radar data) can provide important new sources of information.

It is clear that a landscape-scale approach to modelling fire impacts in erosion response can provide a useful tool for assessing at a strategic level, the impact of various fire management scenarios and climate change on future erosion. The data requirements can be large, and the model requires inputs from research activities across the fields of fire ecology, meteorology, climate change science in addition to hydrology and geomorphology which are at the core of post-fire erosion research. The reliability of the external inputs the model will essentially determine how the model can be applied and its capacity to deliver useful information to land managers. It is therefore important to work across agencies and collaborate to generate data and knowledge which can feed into the proposed erosion modelling framework.

Acknowledgements

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