Background briefings on emerging issues for fire managers from AFAC and Bushfire CRC.

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FIRE NOTE

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EROSION RISK TO WATER RESOURCES IN FIRE AND RAINFALL REGIMES

SUMMARY

Erosion and local flooding after fire in mountainous terrain can have adverse impacts on water resources and infrastructure. Research in this area has primarily been focused around i) the impacts of fire on soil physical properties, ii) the underlying runoff and erosion processes and iii) catchment scale geomorphic and hydrologic responses.

These aspects of the risk picture represent *post-fire* effects and are all related to the vulnerability of the landscape to the impacts of fires with varying severities. An understanding of landscape vulnerability to fire impacts provides the basis on which to predict erosion once a fire has already occurred. However, there are few (if any) studies that aim to quantify changes in risk *over time* under variable fire and rainfall regimes. The fire regime represents an important component of the overall risk, especially given the strong influence of management activities and climate change on fire regimes. In this Fire Note we provide a summary of the factors that determine the level of risk under different fire and rainfall regimes. We then present a conceptual model of risk and provide a framework for incorporating fire and rainfall processes in the representation of risk.

ABOUT THIS PROJECT

This research is part of the Bushfire CRC Extension *Fire in the landscape* project *Managing the threat* and aims to develop better tools for predicting risks associated with erosion and water quality impacts from burnt areas.

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CONTEXT

The potential impacts from post-fire erosion on water quality are well documented in the literature (for example, Smith *et al* 2011). We are interested in predicting how the magnitude and frequency of these impacts change in response to variable fire regimes and prescribed burning.

BACKGROUND

Erosion after wildfire can be predicted using statistical or physical based models which translate a rainfall event into a sediment yield given information on burn severity and catchment properties of the area in question (Cannon *et al* 2010; Robichaud *et al* 2007).

These models predict magnitude of erosion events once a fire has occurred but are unable to provide information on the overall risk when fire and rainfall regimes are treated as variables. This is an important limitation of existing tools, especially when risk is assessed at a strategic level where prescribed burning and changing fire regimes are important elements of the risk picture.

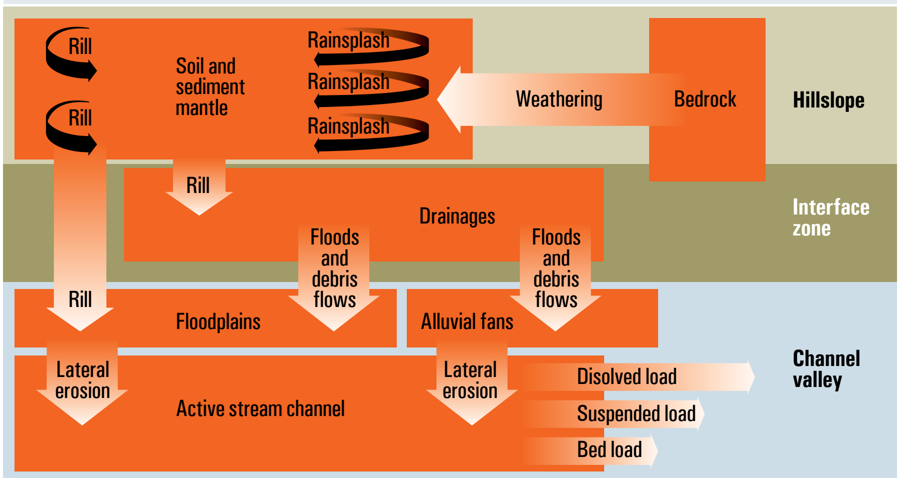
How does a shift in wildfire regime influence the frequency and magnitude of water quality impacts? How does this risk respond to different fuel management strategies? These are questions that land managers typically face during strategic planning and policy development where short and long term outcomes are assessed in a complex environment with multiple stakeholders.

FIRE AND EROSION – WHAT'S THE ISSUE?

Increased erosion and sediment export from burnt catchments has been documented across fire-prone ecosystems in mountainous terrain (Lane *et al* 2006; Moody and Martin 2009). Process-based research on runoff and erosion processes and fire effect on soil properties can show that this increase in erosion is attributed to:

i. Increased surface runoff and peak flows due to removal of vegetation, reduced hydraulic roughness, and

Figure 1



the reduced infiltration rates of burnt soils.

ii. Reduced resistance to erosion due to vegetation removal, the addition of vegetative ash and reduced soil cohesion.

Post-fire impacts on water quality occur 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 (nitrogen, phosphorous), trace elements (iron, manganese, arsenic, chromium, aluminium, barium and lead) and solutes (sodium ions, chlorine ions and sulphate (Smith *et al* 2011)). While the transfer of pollutants can occur through both surface and sub-surface 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; Nyman *et al* 2011) See **Figure 1,** adapted from Moody and Martin 2009.

Post fire erosion events often occur episodically in patches and can be viewed as discrete events in space and time, in some ways a similar manner to landslides (Miller *et al.* 2003). However, there are large spatial and temporal uncertainties associated with the transfer of sediment and pollutants from a source (or patch) to a defined asset or point of impact. These uncertainties are related to the change in transfer processes with increasing spatial scale. Figure 1 illustrates how fluvial transfer processes operate in the various stores of sediment within the catchment.

Surface runoff and short duration events dominate the transfer process in uplands catchments whereas at larger scales the flow-routing, subsurface runoff and floodplain structure play a more important role. If fire impacts on erosion are most pronounced at scales where surface processes dominate, then the initial water quality perturbation at any position within the catchment is ultimately linked to the supply of constituents from patchy source areas in headwaters.

QUANTIFYING RISK TO WATER RESOURCES – WHAT INFORMATION DO LAND MANAGERS DEMAND?

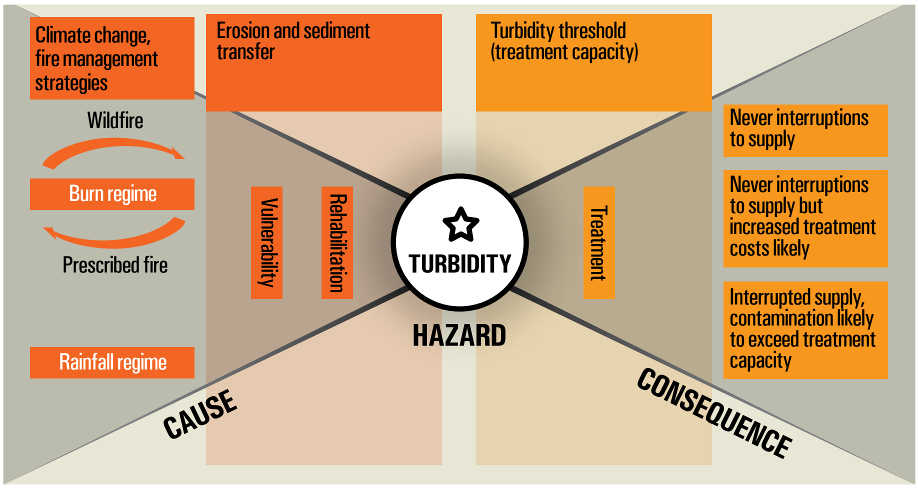
The risk of water quality impacts can be assessed in different contexts depending on the dominant processes that operate at the temporal and spatial scale at which events and activities are defined.

From an operational perspective, the fire and land management activities influence risk through erosion mitigation works, the timing of prescribed fire and the pattern of burn in relation to drainages. Here, research can address changes in risk in response to erosion control works (such as Robichaud *et al* 2007), burn patterns and the connectivity between streams and drainages (Moody *et al* 2008) .

At a strategic level, the risk is influenced by climate change, resources allocated towards fire suppression, annual prescribed fire targets, strategic fuel reduction burns and other regional fire management strategies. Here research can address questions relating to the change in risk as a result of more frequent fire (Istanbulluoglu *et al* 2004).

The bow and tie diagram in **Figure 2** describes the risk picture by linking causes (fire and rainfall) to the hazard and the potential consequences to water supply reservoirs. The horizontal bars represent causes and consequence, vertical bars represent controls such as the landscape vulnerability, treatment capacity or post-fire rehabilitation activities. The star represents point of impact.

Figure 2



END USER STATEMENT

"I see this research developing an operational tool that will help solve one of the major issues faced by land managers across the world – how to predict the likely erosion responses to different fire regimes and weather patterns over a period of time. This type of information is critical for the Rapid Assessment Team Surveys as it will identify "hot spots" for immediate treatment in an effort to prevent major adverse damage to water quality, infrastructure and human life. Of even more importance will be the application of this tool in the planning stages of prescribed burning where sensitive areas can be identified before placing planned fire into the landscape."

– Neil Cooper, Manager, Fire Management Unit, ACT Parks & Conservation Service

Quantifying the total risk to water supply is clearly a complicated task requiring information on the natural fire and rainfall regimes; the susceptibility of landscapes to post-fire erosion; spatiotemporal transfer processes and the vulnerability of various assets to water quality impacts. Climate change, fire management and mitigation strategies further complicate the risk picture.

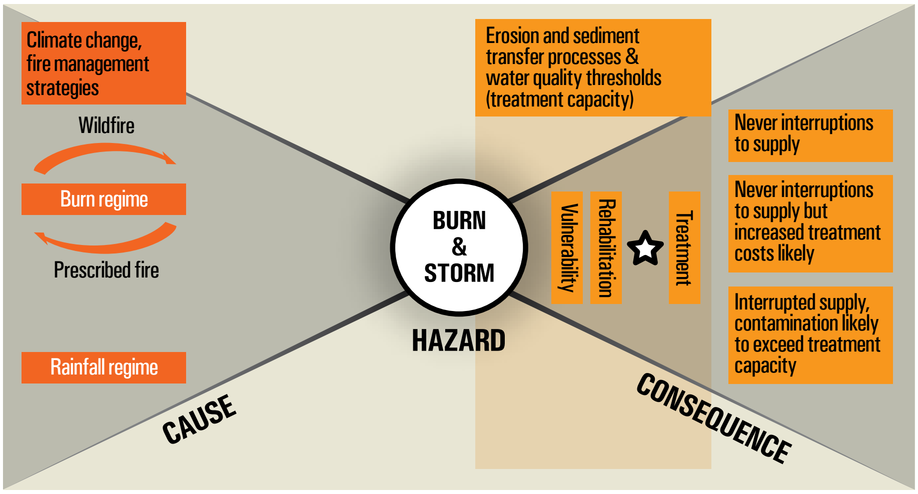
Fire and erosion as geophysical processes are associated with large statistical uncertainties (stemming from natural variability and stochastic processes) and epistemic uncertainties (stemming from the lack of perfect knowledge).

Statistical uncertainties are brought to the system through the random, spatial and temporal variability that is typically associated with climate and bio-physical systems such as fire regimes and hydrological processes. These uncertainties reflect reality and can be incorporated into a modelling environment without loss of predictive power.

Epistemic uncertainties 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 (such as water quality impact). In **Figure 2**, 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.

Large uncertainties can obscure the signal from real effects in a model. In **Figure 2** for instance, the *hazard* is defined as the turbidity

Figure 3



of water in the reservoir (frequency and magnitude of sediment delivery) which is also the impact. Under this scenario, *how does the fire regime influence the hazard?*

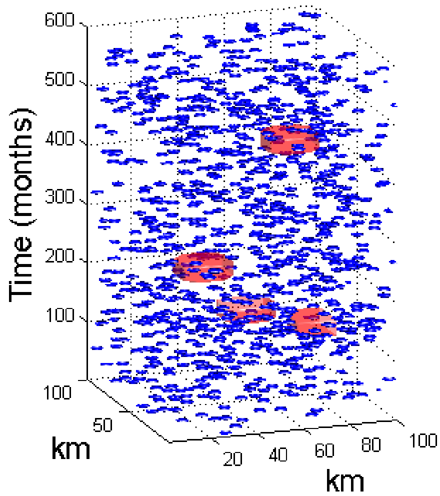
The large uncertainty associated with the controls (landscape vulnerability and rehabilitation) means that it is difficult to detect the effect of a changing fire regime on the hazard as it is defined here. The model would need to estimate the sediment delivery from the range of all possible (random) combinations of fire and rainfall events, an exercise requiring large number of parameters (equals uncertainties) and modelling steps (equals more uncertainties).

An alternative would be to view the hazard as the rate of intersection between rainfall events (storms) and burnt areas (**Figure 3**). Here, the hazard translates into a consequence via landscape vulnerability, mitigation and treatment capacity. This means that a flat terrain with frequent fire and storms (such as savanna) 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 processes are kept constant, then any change in hazard would be proportional to the change in overall risk.

With this definition of hazard, the risk model is therefore more effective at addressing questions relating to long term effects of climate change and strategic fire management on risk. However, if the interest is precise predictions of contamination following a wildfire or the effect of burn patterns on risk, then the hazard is better defined by some measure of sediment delivery to the reservoir (for example **Figure 2**).

Figure 4



A COMBINED MODEL OF STORMS AND FIRE DISTURBANCE

If erosion events are viewed as "episodic patches of activity" (Miller *et al* 2003) then the erosion risk at a given point in time is determined by the episodicity, the patchiness, and the activity (the erosion process itself). Both patchiness and episodicity are stochastic properties which are determined by the spatial and temporal intersections between rainfall and burn areas. The intersections determine both the frequency and the area where erosion is likely to occur. The properties of the intersection (area and frequency) for different storm and fire intensities are therefore important measures of how landscapes become primed in time and space for a particular erosion response.

At a landscape scale, wildfire and rainfall operate as independent stochastic processes both in space and time **(Figure 4).** Each intersection represents an area consisting of the joint burn and rainfall properties including the burn severity, the time since fire and the rainfall intensity and duration. The size of these intersections, the frequency with which they occur, and their joint properties

BREAKOUT BOX: SPACE AND TIME

Fire and rainfall processes operate in a three-dimensional space where the first two dimensions are space (km^2) and the third is time (years) (see **Figure 4).** The set V represents the catchment for a single year, and the model aims to capture the intersection or hazard, R;

R = V ∩ burnt area x duration ∩ stormy area x duration

The duration of a fire is the time it takes for the vegetation to recover (a couple of years). The volume of R, that is ||R|| represents the average annual area where fire and rainfall satisfy the conditions required for a particular erosion event to occur. If λ=fire event rate (per unit area and unit time); μ=storm event rate (per unit area and unit time); α=E||fire event|| (in km^2 x years); and β=E||rainfall event|| (in km^2 x years), it can be shown that;

$$\mathrm{E}\|R\| = \|\Omega\|(1-e^{-\lambda\alpha})(1-e^{-\mu\beta}).$$

The expected area of intersection ||R|| is a measure of hazard that is independent of the landscape vulnerability and the sediment transfer processes that occur following fire. Under this representation, the total risk is a function of both the hazard (intersections) and the vulnerability (erosion and sediment transfer processes). Jones *et al* (2012) were specifically interested in debris flows in Eucalypt forest of south-east Australia and therefore used a known 30-minute rainfall threshold for post-fire debris flow initiation as a measure of vulnerability. Other thresholds may apply for different environments and processes. The model can be extended to incorporate effects of fire severity, recovery and prescribed fire regimes on the annual hazard (area of intersection) associated with post-fire erosion.

are determined by the parameters that define the rainfall and the fire regime. The intersection between fire and rainfall regime will determine the frequency and magnitude of erosion events over time.

As spatial and temporal stochastic processes, both rainfall and fire regimes have been modelled separately using space-time Poisson point process modelling framework (Cox and Isham 1988; Podur *et al* 2010). Two independent Poisson processes operating in space can be simulated simultaneously and explored analytically using coverage models. This modelling approach has applications in a number of fields including wireless communication and cell biology. In the context of fire and erosion (Jones *et al* 2012) developed a coverage model for burnt forest and convective storms using two independent germ-grain processes, one for storms and another for fires (see Breakout box).

FUTURE DIRECTIONS

Both rainfall and fire represent complex landscape processes which vary across landscapes and over time. In order to model these interactions more information is needed on:

1) The spatial and temporal properties of fire and rainfall. A spatial and temporal representation of rainfall requires information on the frequency of events, the intensity and duration of events and their spatial distribution. Fires represent hydrological perturbations which appear as a mosaic in the landscape. Both the measurement and modelling of these processes is a challenge for future research.
2) The effect of prescribed burning and climate change on wildfire regimes. Prescribed fire means that perturbations appear more frequently in the landscape. Modelling efforts should aim to incorporate the linkage between wildfire and prescribed fire and show how the risk to water resources responds to different fire management strategies.
3) Landscape scale vulnerability and sensitivity to fire impacts. 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 ecoregion (or functional response units) where fire effects can be directly linked to hydrological perturbations using a measure of sensitivity to fire impacts.

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