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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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Rethinking the fuel – fire relationship

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Abstract.

Recent advances in the understanding of fire behaviour and the effectiveness of fire management techniques present a number of major new challenges for fire and incident management. The Forest Flammability Model addresses these challenges by characterising fuels with physical measurements of plants rather than indices or approximations. Fuel is described as a discontinuous array of fuel elements with spaces that must be crossed by fire for new fuels to become available. The implications of this are that fire behaviour can change very rapidly with even minor changes in factors such as slope or wind speed, and that vegetation can also act to slow fire spread by reducing wind speed or maintaining more moist fuels. The Forest Flammability Model quantifies these effects, providing improved accuracy in fire behaviour forecasts and identifying new options for fuel management that take into account the effect of forest structure and seral stages on fire spread and intensity.

Additional keywords: Fire behaviour, fuel management, prescribed burning, fire ecology, Forest Flammability Model, climate change

Introduction

Recent work quantifying the effectiveness of fuel treatments for reducing the impact of fire in the landscape has identified the need to re-examine our understandings of the fire-fuel relationship. Loehle (2004) quantified the assumed effectiveness of prescribed burning via the modelling of 'leverage' - the relative reduction in wildfire area for each unit area of prescribed burning. Assuming that fuel reduced areas would not re-burn; each treated cell was found to protect an area in its 'shadow', so that strategically placed prescribed burns produced a leverage of 11 cells protected for each cell treated - a leverage factor of 11. In this sense, prescribed burning could be described as burning a small area to protect a large area and therefore clearly an effective tool for risk management. When the assumed effectiveness of such burns was compared to actual measurements however, the reality was sobering. In the largest such study to date, Boer *et al* (2009) found that the leverage for a prescription burnt area of SW Western Australia was only 0.25. Although the fuel treatments did have an effect on the size of bushfires, Loehle's assumed efficacy of prescribed burning was up to 44 times greater than the measured reality. Very slightly stronger leverage values have been found for forest in the Sydney sandstone (Price and Bradstock 2010), but no study has yet identified a forest community where the introduction of prescribed fire has not increased the total area burnt each year. This has significant implications for landscape values such as catchment management, carbon accounting, smoke production and biodiversity, as well as for the protection of built structures. Leverage does not account for reductions in fire severity or intensity, but as the leverage was measured from a site where active fire suppression also took place, this value of 0.25 indicates that on average, unplanned fires were of sufficient intensity that suppression efforts were unable to contain them over three quarters of any prescription-burnt area.

Although leverage studies do provide an objective measure of prescribed burn efficacy, the practice of contrasting 'young', recently burnt fuels with 'old' long unburnt fuels is fundamentally flawed. The premise for this is the fuel-age paradigm (Zedler and Sieger 2000) - an assumption that forest flammability increases with age. In their examination of prescribed burn efficacy, Fernandes and Botelho (2003) found that "…post-treatment recovery can be so fast that fuel management may be futile or even counter-productive in some fuel types" and that it "leads to the conclusion that the fuel/age paradigm is a simplification, and that the hazard reduction effectiveness of prescription burning will vary by ecosystem (or fuel type) and according to the relative impacts of fuels and weather on fire behaviour." If this is the case, it becomes clear that the leverage when measured across a landscape is likely to be an average of areas where prescribed burns were more effective along with other areas where burns were less effective or counter-productive. If the efficacy of prescribed burning can be identified for specific forest communities then, it may be possible to improve fuel management in general by utilising prescribed fire where it is most effective, and by using other approaches where it is ineffective or counter-productive.

Fundamental to achieving this is the way that the relationship between fine fuels and fire behaviour is understood. McArthur (1967) asserted that fuel load and rate of spread were directly related, so that halving the fuel load would result in a halving of fire spread rate. This concept that the weight of fuels determines the flammability of a forest remains a dominant view across Australia, repeatedly reaffirmed in popular literature (e.g. McCaw *et al* 2008, Attiwill *et al* 2009) and providing theoretical justification to the fuel age paradigm. The reality is however that successive peer-reviewed studies since the 1940's have consistently demonstrated that no such relationship exists (Fons 1946, Fang and Steward 1969, Wolff *et al* 1991, McAlpine 1995, Burrows 1999), that is, that fuel load and head fire rate of spread are unrelated or have such a weak relationship as to be unworthy of consideration in fire behaviour modelling. As surface fine fuels typically increase following the same negative exponential pattern regardless of forest type (e.g. Hamilton 1964, McColl 1966, Ashton 1975, Hutchings and Oswald 1975, Raison *et al* 1986, Burrows & McCaw 1990, McCaw 1997, Gould *et al* 2007), any attempt to reduce flammability premised on the goal of reducing the fuel load therefore imposes an identical view of flammability dynamics across all forests; a view which runs counter to the empirical evidence and has been demonstrated to be significantly less effective than expected. If fuel management is to be made more effective then, it is critical that an evidence-based understanding of the fuel-flammability relationship is adopted so that the different dynamics between ecosystems can be identified and quantified. Effective fuel management requires that we no longer see Australian forests as just “the bush” with one management tool to fit all. This is consistent with Australia’s history of Indigenous fire management, which was characterised by specific approaches in different environments (Zylstra 2006*a*, 2011*a*).

The Forest Flammability Model

The Forest Flammability Model (FFM, Zylstra 2011*a*) was developed in response to this need as part of the Bushfire CRC fuel and risk management studies (Zylstra 2009). The FFM adopts a semi-physical approach to modelling fire behaviour that examines the interactions between fire and all potential fuels in the array using a dynamic, complex systems approach based primarily on convective heat transfer in the context of forest geometry and the principles of flammability (Gill and Zylstra 2005). Surface fuels are treated as the baseline stratum for fire spread, providing a ‘pilot flame’ which is modelled using Burrows (1999) empirical surface spread model. The trajectory for the convective plume is based on flame length and wind speed (Van Wagner 1973), with limits imposed by geometrically calculated blocking effects on air entrainment due to slope. Potential fuels in the higher strata are exposed to a temperature which decreases along the plume according to Weber *et al* (1995), based on distances defined by the geometry of the plants. Ignition of new fuels occurs if the ignition delay time (Anderson 1970) of the leaves is exceeded by the flame duration, where ignition delay time was modelled ($R^2 = 0.90$) across multiple species based on temperature, leaf thickness and moisture content using the experimental procedure of Gill and Moore (1996). Flame duration for surface fuels was based on Burrows (2001), and modelled across species for foliage ($R^2 = 0.74$) based on leaf moisture and cross-section area. The depth of ignition into the exposed foliage was determined iteratively for a one-second time step, then the new flame length calculated from the existing flame minus any expired flame and with new burning leaves added. The length of flame from burning leaves was modelled ($R^2=0.83$) across species based on leaf surface area, and the methods for this and flame duration experiments are described in Zylstra (2006*b*). Flames burning in close proximity were merged to produce a longer flame due to blocked air entrainment and heat feedback (Thomas, 1963, Thomas *et al* 1965, Huffman *et* al 1967, Steward 1970, Chigier and Apak 1975, Tewarson 1980, Gill 1990, Heskestad 1998, Weng *et al* 2004, Liu *et al* 2009). The increased flame length was modelled due to lateral effects using Gill (1990), and due to longitudinal effects using Mitler and Steckler (1995).

This approach has the advantage of being grounded in observable, physically explicable phenomena, and demonstrates that the characteristics of fire behaviour are determined as much by the spaces between fuels as they are by the quantity of fuels. Although the forest from floor to canopy may contain an enormous quantity of potential fuel, if fire is unable to bridge gaps between strata, then the higher fuels are unavailable. Significantly however, unavailable fuels still affect fire behaviour by determining the ‘fuel environment’. Foliage in higher strata directly affects the probability of fire occurrence and the behaviour of fire in dead surface fuels by shading those fuels and thereby affecting the temperature, moisture content and drying rates (e.g. Van Wagner 1969, Viney 1991, and Matthews 2006). Even more significantly, the density and height of foliage in these strata directly reduces the wind speed at lower levels (McArthur 1962, 1966, Cionco *et al* 1963, 1972, 1978, Albini 1981) so that flames in the lower strata are more upright and convective heat is directed upward rather than forward, slowing fire spread. Rather than subjectively applying wind reduction factors as per McArthur (1962, 1966), the ‘canopy flow index’ in the model of Cionco *et al* (1963) was developed, extending work by Greene and Johnson (1996) and Wang and Cionco (2007) so that the speed of wind can be calculated for any point in the vertical profile of a fuel array based upon the dimensions and leaf area index of fuels above that point.

The FFM has received some validation to date (Zylstra 2011*a*), demonstrating lower mean absolute errors than earlier empirical models for both rates of spread and flame heights (table 1). Although this has provided statistically significant improvement in some cases, further validation is ongoing to identify specific strengths and weaknesses.

Implications for fuel and risk management

The implications of the FFM for fuel management are primarily that the focus is shifted from reducing fuel quantity to managing the fuel structure and environment. Because fire is a complex system, finding widespread rules to achieve these goals is not simple as changes in one area may produce positive or negative feedbacks to other areas. For example, a sensitivity analysis of the model (Zylstra 2011*b*) which considered both mature and regrowth Alpine Snowgum (*Eucalyptus niphophila*, figures 1 & 2) found that elevated levels of dead material in the shrub strata increased the mean rate of spread in the mature forest, but slowed fire spread in the regrowth forest. Dead material is generally drier than live material and therefore burns more readily producing greater flame lengths and consequently more upright flames. In mature forest this increased the incidence of active crown fires, where loss of crown foliage facilitated access of wind to the lower strata. In regrowth forest however, the absence of a tree canopy removed this influence, so that the more upright flame simply reduced the forward transfer of convective heat.

Table 1. Mean absolute error for the FFM in comparison with three empirical models (from Zylstra 2011*a*). Models were tested against eight fires ranging from low to extreme intensity to assess rates of spread, and against 10 fires of low to extreme intensity to assess flame heights. Significance was assessed using a paired *t*-test to determine whether the error margin in the model was higher than that of the FFM.

	RATE OF SPREAD		**FLAME HEIGHT**	
MODEL	**Mean error**	**Significance**	**Mean error**	**Significance**
McArthur (1962)	287%	N.S.	111%	N.S.
McArthur (1967)	843%	95.0%	528%	95.0%
Gould *et al* (2007)	349%	90.0%	106%	N.S.

FFM	**69%**	**46%**

Figure 1. Six year-old regrowth Snowgum forest

Figure 2. Long unburnt (50 year-old) Snowgum forest

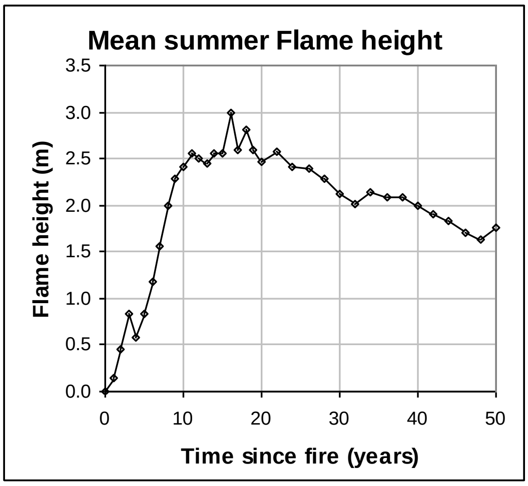

Figure 3. Mean summer flame height modelled for one summer in Snowgum forest on a 17 degree slope. Source: (Zylstra 2011*a*)

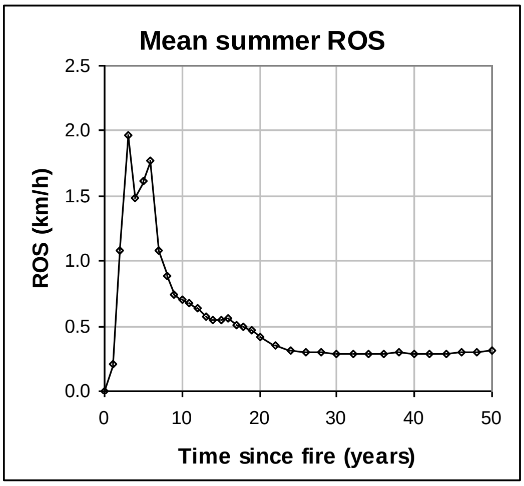

Figure 4. Mean summer rate of spread modelled for one summer in Snowgum forest on a 17 degree slope. Source: Zylstra (2011*a*)

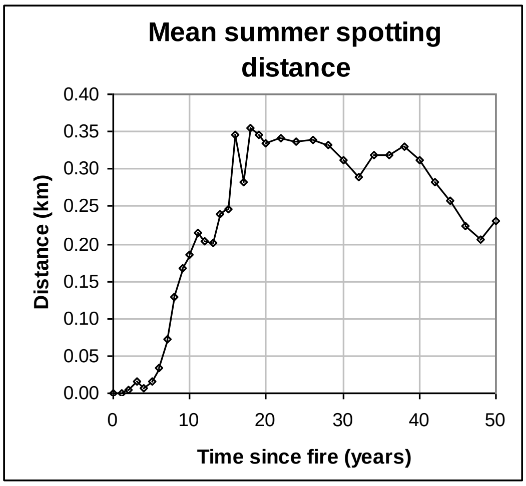

Figure 5. Mean summer spotting distance modelled for one summer in Snowgum forest on a 17 degree slope. Source: (Zylstra 2011*a*)

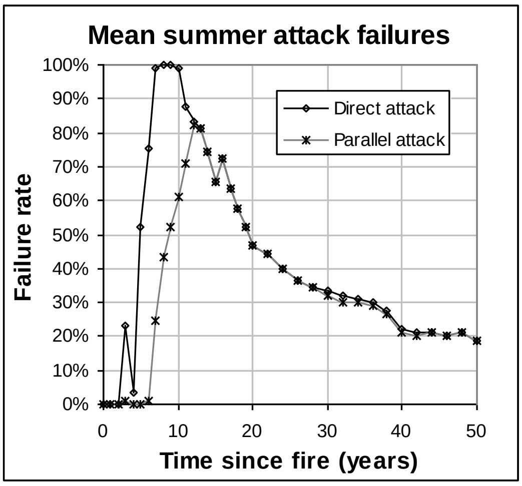

Figure 6. Percentage of a summer where direct and parallel attack methods are expected to fail, modelled for one summer in Snowgum forest on a 17 degree slope. Source: Zylstra (2011*a*)

In order to overcome such complexities, the FFM can be used to develop age-flammability profiles which examine typical weather conditions for a site, considering the changes that are expected based on the known post-fire succession of the community. Such an analysis of the Snowgum community (Zylstra 2011*a*) identified three stages in the regrowth of the forest – young fuels with low rates of spread and flame heights for the first few years following the fire, a regrowth phase of heightened flammability and a long lasting mature phase where rates of spread and frequency of attack failure rapidly decreased to very low levels but mean flame heights and spotting distances declined more gradually (figures 3 to 6). This pattern was similar to that observed in the Dee Vee study as part of the Project Vesta experiments (Gould *et al* 2007, McCaw *et al* 2008), but was more pronounced and determined primarily by the proximity of the regenerating canopy to the lower fuels and its capacity to remain unburnt and thereby reduce wind speeds at the lower fuels. The sensitivity analysis (Zylstra 2011*b*) found that across six different communities, the capacity for midstorey and canopy foliage to slow wind speeds at lower levels was by far the most influential factor determining the flammability of a forest.

The differences in these responses highlight three important points:

If fuel structure and environment are considered, the fuel-age paradigm does not necessarily hold true; that is, flammability may actually decrease with time since fire in some circumstances. Effective fuel management should focus primarily on the way that treatments influence fuel structure and environment over time.

Different aspects of fire behaviour do not necessarily correlate with each other. Effective fire management should identify the specific fire behaviour outcome desired (e.g. reduced flame height or increased direct attack success) and target management to the fuel age that will best achieve this.

Effective fuel management needs to be decisive. Either very frequent fire or active fire exclusion would have achieved similar outcomes for rates of spread for example, but a compromise frequency (e.g. every ten years) would only serve to maintain the forest at its most flammable stage. It should be noted that very frequent fire may have other effects that are not captured here; for example whether planned or unplanned, fire promotes topsoil loss (Smith and Dragovich 2008) which can result in a shift from grasses toward shrubs in this environment (Wimbush and Costin 1979, Williams 1992), which will in turn affect the flammability. Such decisions need to be grounded in quantitative risk assessment so that the actual costs and benefits are compared objectively.

By including multiple aspects of plant and forest structure and physiology, the FFM provides a mechanism by which the effects of external environmental influences on bushfire risk can also be better quantified. The moisture content of some plant species for example is heavily influenced by temperatures averaged over the preceding week, while other species respond primarily to soil moisture (Zylstra 2011*a*). The influence of a hot day following a protracted heatwave compared to that of an isolated event can therefore be compared directly, or contrasted with the effects that drought has on fire behaviour through the drying of different plant species. Changes in temperature and atmospheric CO_2 levels also affect features such as leaf dimensions and the capacity of some plants to grow in shaded areas (Ashton 1975, Ashton and Turner 1979), and the occurrence of heavy frosts imposes limits to the distribution of some species (Newman 1954, Moore and Williams 1976). These factors are observably changing as a result of anthropogenic global warming (Rosenzweig *et al* 2007) and the FFM provides a tool by which the impact of such changes can be modelled. Increased temperature for example may result in the earlier seasonal growth of large leaves in some species (Ashton 1975). This may in turn increase the flammability of a forest as longer leaves produce larger flames (Zylstra 2006*b*, 2011*a*), or may decrease flammability by providing more shade (Matthews 2006) and reduced wind speed in lower plant strata (Cionco 1972). As these factors are part of a complex system of feedbacks and interactions, it is impossible to predict the outcome without careful modelling and it certainly cannot be addressed with a simplistic attention to fuel load.

Existing responses

The over-simplification of the fuel load argument has been partly recognised through industry tools (Hines *et al* 2010), which consider some aspects of fuel structure such as shrub density and assign different weightings to fuels in different strata. Major structural and environmental feedbacks such as canopy density and separation from lower strata are not captured however, so the overall effect is still the consideration of fuel load, albeit weighted by its location in the array. While Hines *et al* (2010) does not provide a connection between fuels and fire behaviour, Gould *et al* (2007) used a similar approach to differentially weight fuels in three different strata using two fuel load parameters and two wholly structural parameters, and provide a fuel-fire connection. This has produced large improvements in predictive accuracy compared to McArthur (1967, Table 1). Canopy separation from lower strata is partially inferred by the inclusion of shrub height; however without consideration of other critical structural and environmental effects as outlined earlier the model is also unlikely to identify major discrepancies from the fuel-age paradigm.

In applied risk management applications, fuel load is still very frequently the sole determining factor. Under Australian Standard AS 3959_2009, specific issues of risk management around built structures are still assessed on fuel load alone, as are some other tools currently being developed to determine optimal placement and extent of prescribed burning in the landscape for likelihood assessments (e.g. Tolhurst *et al* 2009). Bushfire threat at the urban interface is currently being re-examined using the FFM (Zylstra 2011*c*) as part of the Bushfire CRC Fire Impact and Risk Evaluation Decision Support Tool (F.I.R.E_D.S.T) with the intention of both improving accuracy of assessments and of informing more effective fuel management. Fuel management in the landscape however continues to be informed by tools that do not incorporate the major factors of fuel structure and environment such as canopy density and the continuity of fuels to the canopy. Consequently, those areas where the introduction of fire may be “futile or even counter-productive” (Fernandes and Botleho 2003) cannot yet be effectively identified, rendering prescribed burning programs less effective than they could be.

Model implementation

The main obstacle to implementation at this stage is the fact that the FFM utilises many more fuel inputs than other Australian fire models. This however can be overcome by a shift in thinking. The FFM identifies that many factors in the structure and physiology of plants and forests work together to affect their flammability, so what is needed is not more intensive fuel measurement but better measurement of forests in general. Because the fuel parameters are direct measurements rather than subjective scores or visual estimates, all parameters are either measurable from herbarium specimens or via remote sensing methods (Zylstra 2011*b*). Using a combination of these methods to produce a central database of static species-specific traits such as leaf dimensions along with remotely sensed imagery from either satellite sensors such as

QuickBird or airborne sensors such as LiDAR or ADS40 imagery, it may become possible to move from a culture of subjective point measurements obtained by labour-intensive field survey toward objective landscape-scale measurement. The mean sensitivity of the parameters was also very low (0.18, Zylstra 2011*b*) compared to 1.00 for the McArthur meter, allowing for considerable error in measurements.

Natural variability in forest structure produces variability in fire behaviour, so collection of the variability in parameters will allow ensemble modelling of behaviour with statistically defined limits. This produces a trade-off between mapping resolution and predictive precision, so that finer mapping scales will produce a narrower range of potential outcomes. In this way, the desired level of accuracy can be used to determine the mapping resolution needed for an area.

Conclusions

Although tools such as the Overall Fuel Hazard Assessment Guide (Hines *et al* 2010) are beginning to increase the focus on fuel structure to some extent, fuel environment and many structural elements are not yet considered and the resulting management remains underpinned by the fuel-age paradigm. Popular thinking still describes the objective of fuel management as fuel reduction rather than optimisation of fuel structure and environment (e.g. Adams & Attiwill 2011), and tools used for risk assessment such as the AS 3959_2009 and others currently being developed to determine optimal placement and extent of prescribed burning (e.g. Tolhurst *et al* 2009) remain constrained by McArthur's modelling of fuel load effects on fire behaviour. Because this underlying paradigm persists despite the weight of evidence, fuel management programs have very little capacity to identify the forest communities where prescribed burns will be effective and where they will not, so that empirical analysis of the effectiveness of these programs has demonstrated disappointing results when compared with theoretical expectations. More effective fuel management may be achieved by rejecting the assumption that 'young' fuels are automatically less flammable and instead using an evidence-based approach to identify and manage for an ideal age range. As different measures of fire behaviour or risk do not necessarily correlate, the priority measures should be identified based upon specific objectives for the location and the target age range planned to minimise these.

To this end, the FFM provides a peer-reviewed and scientifically credible tool for understanding and quantifying the complexities involved. By utilising physical measurements of plants, the FFM also provides a means to move away from labour-intensive and subjective point-based generalisations around fuels so that landscape-scale tools such as remote sensing can be adopted. More complex changes to the risk environment such as through climate change can also be treated with the necessary detail and adequately quantified.

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