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Live fuel moisture and wildland fire behaviour

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Abstract

Live fuel moisture content (LFMC) is a parameter that affects the flammability of plants, and the capacity to measure it remotely makes it an accessible variable for use in fire behaviour models. Although the effect of LFMC on the flammability of fuel particles has clear theoretical support however, the way in which this relates to fire behaviour is complex and difficult to quantify so that empirical studies of heath and forest fires at times yield weak or ambiguous results.

This study examines the way in which moisture affects fire behaviour by using a process-based conceptual framework (Zylstra 2011) to identify feedbacks and complexities that may confound empirical analysis.

Z11 links empirically-derived sub-models of flammability characteristics within a dynamic physical framework where heat is transferred convectively across spaces between leaves, branches, plants and plant strata. The ignitability, combustibility and sustainability of flame from burning leaves interacts with the geometry of the fuel array to determine whether flame will spread across horizontal spaces affecting rates of spread, and vertical spaces affecting flame heights.

Factors are identified that should be considered explicitly in experimental design if LFMC is a consideration, and physical arguments presented to show that where such a range of conditions is not present in the experimental design, the results are inadequate to draw conclusions. In some cases, practical considerations will prevent the lighting of experimental fires under the full range of necessary conditions so that the best understanding will be derived from modelling results. In such cases, misleading conclusions will be drawn unless the model can adequately reflect the complexity presented here.

There exists a strong physical argument for the effect of LFMC on fire behaviour, however this effect is not straightforward and will drive threshold changes and feedbacks. Such changes may represent sudden and dangerous escalations in fire behaviour, so understanding and quantifying these is important. Z11 is a model that can calculate such thresholds and can be used to both inform experimental design and risk-based decision making.

Keywords*: Fire behaviour, live fuel moisture, flammability, Forest Flammability Model, complex systems*

1. Introduction

Live fuel moisture content (LFMC) is a readily accessible metric that can be measured to varying levels of precision via remote sensing (Yebra *et al.* 2013). Physical arguments suggest that it has an influence on fire behaviour as the presence of moisture affects the flammability or ignitability, combustibility and sustainability (Anderson 1970) of leaves; however debate exists as to the extent and nature of the influence in field conditions and it is therefore rarely or inadequately considered as a component of fire behaviour modelling.

Ignitability has two components – the minimum temperature of ignition (Philpot 1970) and the time to ignition (Gill and Zylstra 2005). While the minimum temperature or endotherm appears to be a chemical property, time to ignition is the time taken for a leaf to be heated to ignition and relates to both the surface area to volume ratio and the thermal inertia of the leaf. Various studies (e.g. Xanthopoulos and Wakimoto 1993; Weise *et al.* 2005; Madrigal *et al.* 2011) have identified moisture content as a major influence in this, although more recent studies at higher temperatures (Engstrom *et al.* 2004; Fletcher *et al.* 2007) have failed to find a relationship.

While the effect of moisture on particle ignition is widely accepted under most conditions, the

influence of LFMC on fire behaviour as a whole is more complex. It has been strongly implicated in the incidence and scale of fires across several landscape studies (e.g. Schoenberg *et al.* 2003; Chuvieco *et al.* 2009; Dennison and Moritz 2009; Caccamo *et al.* 2012) and identified as a key determinant in the behaviour of fires burning through simple complexes such as heath and shrub lands (Weise, Zhou, *et al.* 2005; Davies *et al.* 2009; Plucinski *et al.* 2010). The interaction however is harder to detect in more complex arrangements. Alexander and Cruz (2013) have summarised the results of a series of laboratory and field experiments looking at LFMC effects on behaviour, noting that the correlation is either ambiguous or non-existent when all studies of heath and crown fires are considered; although its role in facilitating crown fire commencement was not examined.
This paper addresses the conflicts by providing a theoretical analysis of the mechanisms by which moisture affects fire behaviour, describing trends, feedbacks and complexities which may mask correlations in studies that do not specifically account for them.

2. Methods

The role of moisture is described and quantified mathematically through a process-driven model that addresses the limitations identified for laboratory studies. The model is then described conceptually as a basis for explaining anomalous observations, and to provide some guidelines for effective analysis of the relationship.

2.1. Issues to be addressed

Two main concerns have been raised over attempts to model the effect of moisture and other particle flammability properties; these are:

1. *Exaggerated effects of LFMC due to inadequate experimental technique*. Empirical models of time to ignition are frequently constructed using small radiant heat fluxes (Fernandes and Cruz 2012; Alexander and Cruz 2013) when analyses at higher convective fluxes have reported little to no relationship (Engstrom *et al.* 2004; Fletcher *et al.* 2007). In addition, it is at times erroneously assumed that all moisture is evaporated before a leaf ignites (Pickett *et al.* 2010), so that models of time to ignition may over-estimate the effect of LFMC at high temperatures typical of field conditions.
2. *Flawed assumptions*. The flammability of plant parts does not automatically scale to the flammability of the whole plant (Pérez-Harguindeguy *et al.* 2013) or stand (Fernandes and Cruz 2012).

2.2. Model description

The fire behaviour model (Zylstra 2011) hereafter referred to as Z11 currently utilises empirical models of leaf flammability that were developed alongside the main model. The equations for combustibility and sustainability were developed from experiments that utilised candle flames, where the point of heating for the leaves used a measured heat flux of 145kW/m^2 (Hamins *et al.* 2005). This exceeds the values of 61kW/m^2 measured in the field by Silvani and Morandini (2009) and approaches the maximum value of 150kW/m^2 measured by Butler (2010). Both models found a significant influence of leaf moisture, and predicted flame length and duration values for leaves across 10 sclerophyllous species and a wide range of moisture values with R^2 values of 0.87 and 0.74 respectively.
The main concern expressed in the literature however relates to models for time to ignition. Equation 1 used in Z11 was developed across six sclerophyllous species with moisture contents ranging from oven dried to 200% with combined convective and radiative heating to temperatures from 220^{o}C to 700^{o}C, explaining 90% of the variability for the species and conditions studied. Surface area to volume ratio had the effect of regulating the conductance of heat into the leaf so that leaf thickness T and the

number of sides s to the leaf combined with moisture content m to form the ignitability coefficient IC (equation 2). The effect of leaf thickness is thereby negated when moisture is zero. The units for these equations are percent, mm and ^{o}C, and leaves have either two sides when flat or four when terete. Time to ignition is ψ and temperature is t.

$$\varphi = IC97805.26t^{-2.10} + 6452280.04t^{-2.40}$$ Equation 1

$$IC = \frac{mT}{s}$$ Equation 2

Although the temperatures in the muffle furnace used were not as high as those of the Chaparral studies (Engstrom *et al.* 2004; Fletcher *et al.* 2007) and the heat fluxes were not measured; figure 1 demonstrates that when reported moisture and leaf thickness values are used to predict the times to ignition that were measured in these studies, the model of Z11 was well within the target range and moisture content did not artificially slow expected ignition times.

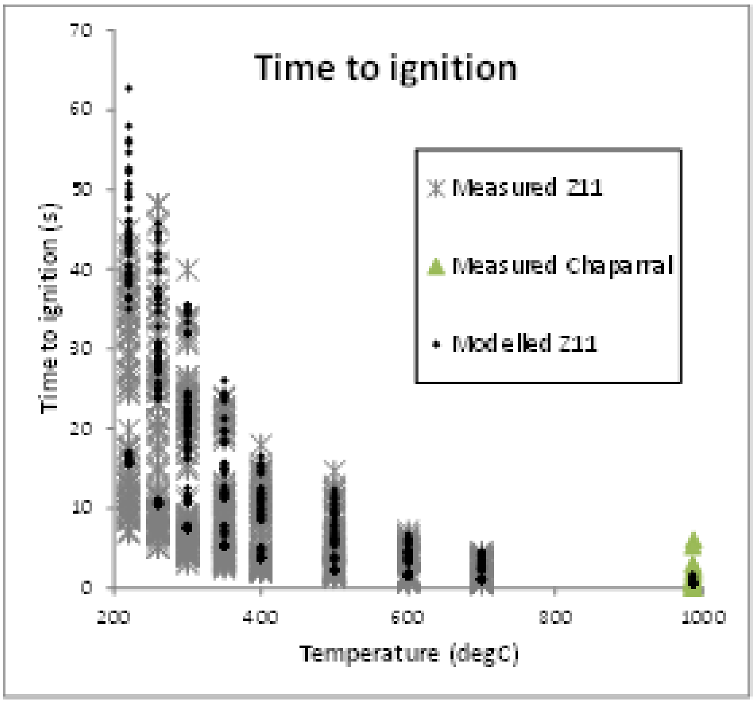

Figure 1. Equation 1 extended to predict the values measured by Engstrom et al. (2004) and Fletcher et al. (2007)

In regard to the second concern, Z11 makes no assumptions about the scaling between leaf flammability and plant or stand flammability, rather this relationship emerges dynamically from a series of interactions calculated in 1s time-steps. Fire propagates in a process analogous to crown fire initiation models such as Xanthopoulos (1990) and Cruz *et al.* (2006), where fuels are ignited by a heat flux that decays across a distance defined by the geometry of the array. Each leaf flammability property explicitly influences propagation as described in Table 1. In this way, the dimensions, position and angle of the flame are adjusted each second according to the capacity for flames to ignite new fuels across spaces between leaves, branches, plants and plant strata, and the time for which these fuels stay ignited.

Table 1. The role of leaf flammability properties in Z11

Flammability component	Influence
Combustibility	The length of flame produced by burning leaves modified by the physics of flame interactions for the number of leaves burning in close proximity defines the flame length for a time-step. Together with the temperature at which these leaves burn, this in turn produces the input to a temperature field. The decay in convective temperature is defined with distance from the base of the flame, and the direction of convective transfer is defined by the angle of the flame as influenced by its length, the wind speed at that point in the forest profile and any blocking effects of the slope.
Sustainability	A cohort of leaves is ignited in each time-step, and these burn for a period of time defined by their sustainability before they extinguish, redefining the flame origin and the total quantity of leaves burning.
Ignitability	Leaves along the vector defined by the flame are exposed to a given temperature defined by their distance from the burning fuels. If this temperature both exceeds the endotherm of the leaves and the time to ignition calculated by equation 1 for that temperature and the ignitability of the leaves is less than the calculation time-step, then the leaves ignite, increasing the quantity of leaves burning. If both conditions are not met, the time-step is considered pre-heating and a proportion of the time to ignition is removed according to the heating received. The leaves are again tested in the next time step.

The way in which the ignitability of a leaf affects flame propagation is shown in figure 2. As the distance increases from the flame base along the *x*-axis, temperature decays along the lower part of the *y*-axis, in this case using the functions given by Weber *et al.* (1995). The time to ignition is modelled against this temperature using equation 1 for a leaf with low ignitability (high moisture content and/or thickness) as shown by the lighter broken line, and for a leaf with high ignitability (low moisture content and/or thickness) by the heavier broken line. At the left of the graph where temperature is highest (such as observed in the chaparral studies), the time to ignition is very short. As temperatures decrease with distance from the flame base, time to ignition increases until it meets the solid horizontal line which marks the time-step used for calculation. The intersection of these lines shows the maximum distance that may be ignited during that time-step. That is, all leaves in a plant crown that lie within this distance will be ignited in that step. As time to ignition is defined by temperature which is in turn defined by distance from the flame base, ignitability can therefore be understood not only as time to ignition, but also as distance to ignition or minimum temperature required to ignite within a given time step.

Equation 1 demonstrates that very high temperatures will indeed overwhelm any small effect of leaf moisture, however high temperatures are not limited to field conditions. Even a candle can produce a temperature of 1400ºC (Gaydon and Wolfhard 1979) and thereby exceed the maximum value recorded by Butler (2010) for a crown fire; but in each case this only corresponds to the hottest part of the flame. As time to ignition equates to distance to ignition or minimum temperature required for ignition within a given time, the effect of moisture is to regulate the distance to which leaves can be ignited. Larger gaps can be crossed and more leaves lit simultaneously when they are drier.

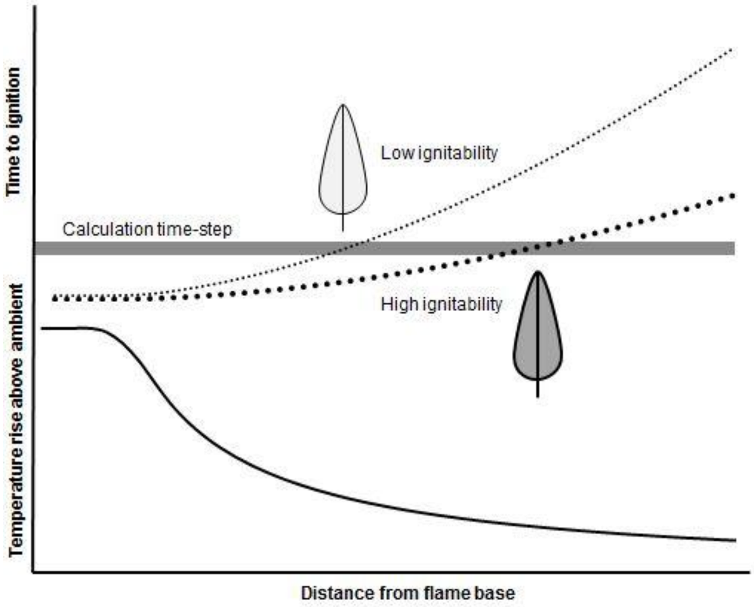

Figure 2. Translating time to ignition into distance to ignition. The curved solid line represents flame temperature, the straight line marks a time-step on the y-axis and the two broken lines mark the time to ignition for two different plant species as calculated using equation 1.

To picture the process, consider a simplified situation where the combustibility and sustainability of leaves are kept constant and can be characterised such that flames are 1.5 times the depth of ignited leaves, the hottest part of any flame is 1300°C and all leaves burn for 2s. Three different LFMC values will be considered (Table 2) for two-sided leaves in a 0.7m tall shrub with a base extending from the ground, and with leaves separated by 4cm. Pre-heating will be ignored for simplicity and no wind will be considered so that flames are vertical. The value 'minimum temp' in Table 2 is the temperature required to ignite the leaves in 1s or less, found by solving Equation 1 for *t*.

Table 2. Ignitability of leaves in the examples

	Moisture 1	**Moisture 2**	**Moisture 3**
Moisture (%ODW)	70%	220%	250%
Thickness (mm)	0.2	0.2	0.2
IC (Eq. 2)	7.0	22.0	25.5
Minimum temp (°C)	850	1200	1260

If all three plants are exposed to an identical heat flux from a pilot flame of 0.3m such as might be achieved from a fire burning surface litter, the distances to minimum temperature found using Weber *et al.* (1995) will be 0.28m, 0.12m and 0.08m respectively. That is, in the span of 1s the bottom 28cm of leaves will be ignited in the driest plant producing a plant flame that extends 1.5 times the depth ignited (42cm) beyond the ignited leaves. In the wettest plant however, only 8cm of the lowest leaves will be ignited, producing a flame extending 12cm. The altered heat fields produced by the new flames will allow flame to propagate in the two drier plants, but in the wettest plant the distance to 1260°C will be less than the separation between leaves and flame will not propagate. As more leaves are ignited in the next second these are added to the total depth of ignited leaves, but because the leaves only burn for 2s the lower cohorts will extinguish in sequence after this time even as new leaves are ignited. The three scenarios are shown in figures 3 to 5.

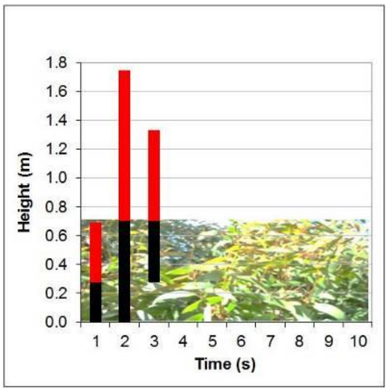

Figure 3. Fire propagation in Moisture 1. Maximum flame height reached is 1.75m, the plant is consumed and flame duration is 3s.

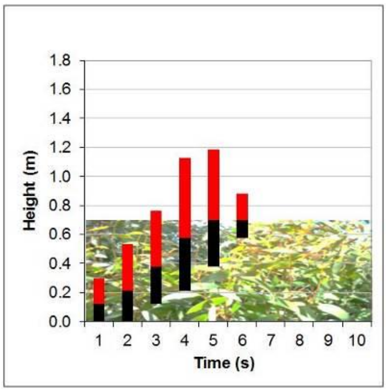

Figure 4. Fire propagation in Moisture 2. Maximum flame height reached is 1.18m, the plant is consumed and flame duration is 6s.

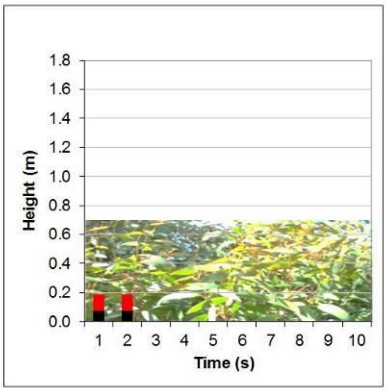

Figure 5. Fire propagation in Moisture 3. Maximum flame height reached is 0.19m, the plant is only partially consumed and flame duration is 2s.

Although these scenarios describe simplified situations and the influence of moisture will be affected to some extent by pre-heating and its effect on combustibility and sustainability of leaves, the basic process by which leaf flammability translates to fire propagation can be understood. Notably, the flammability properties of the leaves did not scale directly to the plant. While only the ignitability of leaves was altered, the sustainability of flame in the plant varied from 2s to 6s and the combustibility varied such that flame heights ranged from 0.19m and 1.75m. In this way, the flammability of plants and stands emerges from numerous factors and should not be assumed from the parts.

3. Model application

The lack of correlation between LFMC and fire behaviour reported for many field experiments requires explanation, however full treatment is impossible without replication of the exact conditions. In the absence of this information, the principles of fire propagation that have been shown will be used to describe a series of behaviours that can confound the observation of trends.

Much work on fire behaviour has focused on propagation through continuous fuel beds such as dead leaf litter; however such observations can be misleading if applied to discontinuous fuels. Plant communities are characterised by gaps between leaves, branches, plants and plant strata, and the bridging of these gaps can result in threshold changes that are not well captured with statistical methods that do not explicitly account for them.

As convective heat transfer occurs along a vector rather than being radiated in all directions, heat can be directed upward across vertical spaces between strata, or horizontally across gaps between plants. The angle of the trajectory is influenced by the size of the flame providing buoyant uplift, the velocity of the wind acting on the flame and the effect of slope in blocking air intake from one side. In both this way and by the tilting of the fuel array in relation to the flame, the effect of slope may not follow expectations established from fires in continuous surface fuels, but may produce threshold changes in the same way as winds do.

The emergent nature of fire behaviour can introduce feedbacks that obscure trends or even produce opposite trends to those of the larger picture. Consider for example the difference in the height of flames produced in figures 3-5. Larger flames are more buoyant and therefore stand more upright against lateral air movement than do smaller flames, so that if wind was added to those scenarios, the differences in flame height may have been even greater due to tilting of the smaller flames.

Tilting of flames however has the effect of directing the convective stream forward rather than upward, and the propagation of flame between plants in the same stratum requires this forward direction of heat. It can be the case then that when plants produce smaller flames due to higher moisture contents, the greater tilting of these flames by the wind facilitates forward propagation with resulting faster rates of spread and larger flames as the amount of fuel burning increases. The lowest wind speeds allowing this spread produce a transitional period where temporarily larger flames pulse - in turn standing upright and still due to their size before partially dying out then leaning forward again to spread in a pulsing pattern. Under stronger wind conditions however, the flame of the drier shrub will also propagate forward in the same way, but as it produces a greater convective burst it will also lead to a faster spreading fire.

This phenomenon which may be called *flame angle feedback* is illustrated in figure 6 for a hypothetical heathland modelled with Z11 under two different moisture treatments where LFMC is equal to 80% in one, and doubled to 160% in the other. Rates of spread (ROS) are initially faster in the moist plants than the dry ones, but as wind speeds increase, fire spreads faster in the dry heath.

This is an important aspect that must be factored into experimental design, as the failure to conduct experiments under conditions that will accommodate this feedback can result in weak or erroneous conclusions. Figure 7 illustrates this by examining the correlation between LFMC and ROS for the two scenarios. If experiments in this heath were conducted with winds that did not exceed about 20km/h, it may be concluded that fires spread faster in more moist heaths. It may in fact require experimental burns in wind speeds significantly greater than this threshold speed before any robust correlation can be found. As operational issues frequently preclude burning under such conditions it may be impossible to provide an empirical answer for this situation, however it should be noted that this threshold is specific only to this scenario and others will apply under different slopes, with different species, plant sizes and spacing.

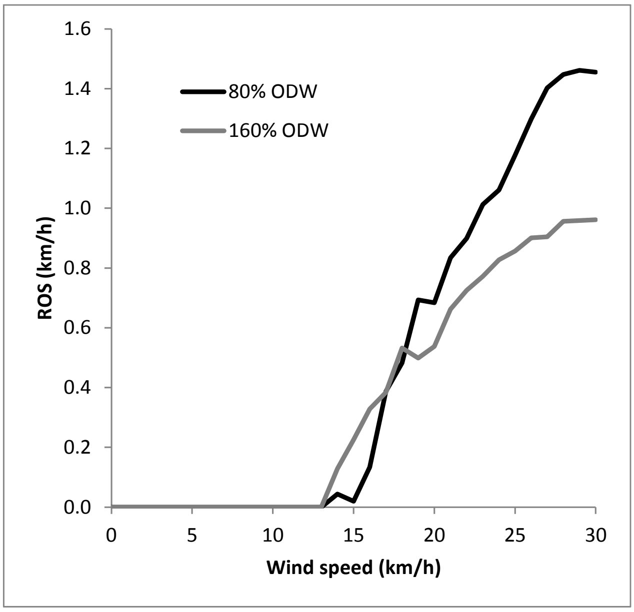

Figure 6. Fire Rate of Spread in two hypothetical heathlands modelled using Z11. Lateral spread initiates under lower wind conditions for the more moist plants, but once initiated, fire spreads faster in the drier plants.

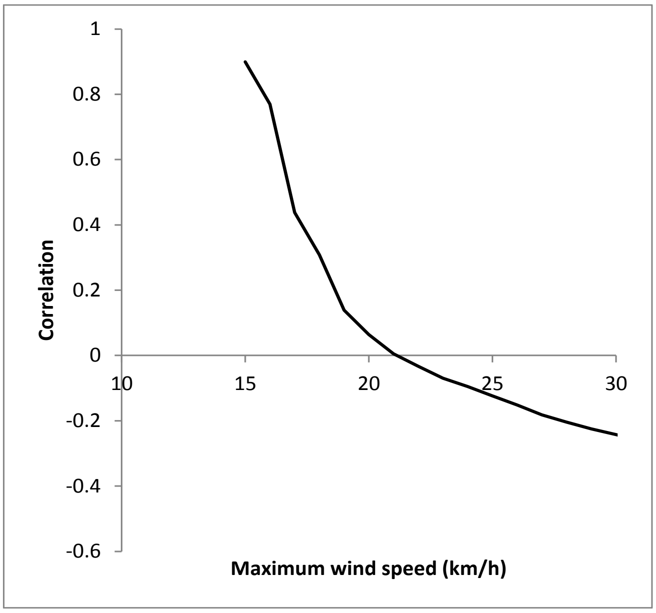

Figure 7. Correlation of ROS with LFMC for the two scenarios in Figure 6. The x-axis indicates the maximum wind speed considered for analysis so that if only fires burning under wind speeds of 20km/h or less are considered, the correlation is positive (i.e. fire spreads faster in more moist fuels). Consideration of higher wind speeds however produces a negative correlation.

Table 3. Summary data from Table 1 in Alexander and Cruz (2013)

Wind speed (km/h)	LFMC (% ODW	ROS (m/min)	Flame height (m)
23	135	16.8	19.8
15	100	10.8	14.8
19	95	27.4	30.5

This relationship is evident in one of the examples reported in Alexander and Cruz (2013), where the results from published fires are summarised in Table 3. As the LFMC is reduced from 135% to 100% the ROS declines along with the flame height, but when the wind speed is increased for a second dry scenario, the ROS and flame height increase to well beyond the value in moist fuels, even though the wind speed remains lower than in this example. Assuming that all other factors are constant, this is exactly the pattern that may be expected if the wind speeds lie across a threshold.

Flame angle feedback becomes more complex when more plant strata are considered, as more vertical gaps between fuels are introduced in the process. High wind speeds may have the effect of tilting the flame so far that crown fire does not initiate (e.g. Luke and McArthur 1978; Buckley 1990) and the fire slows down, or if tilting further forward in a dense shrub layer the greater flame length produced may initiate a crown fire. The response will vary depending again on the flammability, size and density of plants, on the degree of protection from wind provided by the higher strata, and on the vertical gap sizes.

As the length of flame from burning plants relates to the depth of foliage and therefore the number of leaves or quantity of fuels burning, the shape of plant crowns can have an important effect on flame dimensions. In general, the largest flames are produced when the angle of the flame intersects the plant crown at its longest axis, igniting the most leaves. Tall narrow plants will therefore produce the largest flames when the flame angle is close to vertical, so if the leaves are moist and the flame is more easily tilted by wind, the effects of moisture in reducing flame length will be accentuated. Conversely, if the plant is wider than it is tall, smaller initial flames from moist leaves may ultimately ignite more of the plant if directed forward. These effects may however be obscured if plants are in close enough proximity to allow forward spread, as the shape of individual plants will become irrelevant.

4. Discussion

A fundamental tenet of complex systems theory is that such systems are self-organised (Bak *et al.* 1988); that is, behaviours emerge from many interactions and cannot be predicted from initial trends. While broad trends may be identified, specific predictions cannot be made from these alone and the interactions of the various agents must be modelled. Increasing greenhouse gas concentrations warm the planet for example, but the mean temperature of an upcoming season will not be well predicted without knowledge of factors such as the circulation of heat within the system via the Southern Oscillation Index. The interactions of multiple agents can confound individual predictions, so that even though CO_2 levels increase, global temperatures fall for a short period and even though leaves in a forest become drier, fires under some conditions burn with smaller flames and spread more slowly. The presence of feedbacks and threshold changes (also known as criticality or tipping-points) are part of such systems and do not negate the importance of individual factors.

Modelling of fire behaviour as a complex system suggests that the quantity of moisture in plant leaves is an important influence on the behaviour of wildland fires. The scale and direction of its influence will vary markedly with the conditions, the species and the structure of the fuels burning, but the overall effect is that drier plants produce larger, faster fires.

The apparent influence of LFMC on fire behaviour becomes less discernable as fuel arrays increase in complexity - as expected if the system is self-organised. While Zylstra (2011) showed that the evaporation of water explained 90% of the variability in time to ignition for individual leaves and the effect of LFMC was discernable in lab experiments with model shrubs etc; field experiments involving more complex fuel arrays have found little correlation. The larger heat fluxes and temperatures involved fail to explain this; however the feedbacks and threshold changes that can be expected from bottom-up simulation of the processes can provide viable answers for these apparent anomalies.

Attempts to quantify the effect of LFMC empirically therefore must be designed around the location of thresholds and account for the influence of feedbacks; although this will not always be possible due to operational constraints. The most vital component of this is that fires are examined across a broad coverage of wind speeds, with less wind required when burning up steeper slopes.

Where adequate studies cannot be carried out for certain fuel arrays, Alexander and Cruz (2013) propose that appropriate physics-based models can be employed to resolve issues. It will be critical that such models are capable of capturing the complexity described here. The Z11 or Forest Flammability Model used in this study is currently undergoing software development and validation through the Centre for Environmental Risk Management of Bushfires at the University of Wollongong.

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