Assessing the effect of foliar moisture on the spread rate of crown fires

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Abstract. This paper constitutes a digest and critique of the currently available information pertaining to the influence of live fuel or foliar moisture content (FMC) on the spread rate of crown fires in conifer forests and shrublands. We review and discuss the findings from laboratory experiments and field-based fire behaviour studies. Laboratory experimentation with single needles or leaves and small conifer trees has shown an unequivocal effect of FMC on flammability metrics. A much less discernible effect of FMC on crown fire rate of spread was found in the existing set of experimental crown fires carried out in conifer forests and similarly with the far more robust database of experimental fires conducted in shrubland fuel complexes. The high convective and radiant heat fluxes associated with these fires and the lack of appropriate experimental design may have served to mask any effect of FMC or live fuel moisture on the resulting spread rate. Four theoretical functions and one empirical function used to adjust rate of fire spread for the effect of foliar or live fuel moisture were also concurrently examined for their validity over a wide range of FMC conditions with varying outcomes and relevancy. None of these model functions was found suitable for use with respect to dead canopy foliage.

Additional keywords: conifer forest, crowning, dead foliage, fire behaviour, flammability, foliar moisture content, fuel moisture, heat transfer, live fuel moisture, shrubland.

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Introduction

The effect of the moisture content of fine dead fuels such as needle litter on the spread rate of surface fires in forests has been well substantiated in the field and the laboratory many times over the years (e.g. Curry and Fons 1938; Anderson and Rothermel 1965). However, to our knowledge, no field study has been carried out to specifically examine the effect of the moisture content of live fuels on the propagation of high-intensity fires, namely crown fires in conifer forests and shrubland fuel complexes (i.e. fires propagating through the combustion of canopy fuels).

Given that live foliage is the main fuel involved in the canopy fuel layer of crown fires, an understanding of the effect of live fuel moisture on the spread rate and intensity of this type of fire is necessary for proper model development and application. Although the effect of foliar moisture content (FMC, % oven-dry weight basis) on crown fire propagation has not been empirically substantiated as yet (Van Wagner 1998; Cruz et al. 2005), several models have incorporated an explicit function based on (1) heat transfer considerations (Albini 1996; Butler et al. 2004b) or (2) a damping term based on physical logic and related considerations (Van Wagner 1974; Schaaf et al. 2007).

The existing models for predicting crown fire rate of spread (ROS) that incorporate a FMC are based on forests with green or healthy needle foliage. In Canada, for example, FMC is expected to vary from 85 to 120% on a seasonal basis (Forestry Canada Fire Danger Group 1992). On the basis of a review of several studies carried out on North American conifers, Keyes (2006) indicated that FMC values ranged from 73 to 480% depending on species, foliage age and season. However, he considered a FMC of 90 or 100% a ‘prudently conservative’ low default value in assessing or predicting crown fire behaviour. This is supported by the comment of Chandler et al. (1983, p. 35) that ‘A general rule of thumb with regard to living foliage moisture is that crown fire potential in conifers is high whenever needle moisture content drops below 100 percent of dry weight’.

An important departure from normal FMC conditions are the very low levels (e.g. down to ~7%) associated with forests subjected to insect attacks such as the mountain pine beetle (Dendroctonus ponderosae) (W. G. Page, Utah State University, pers. comm., 2012). Low FMC levels can also be induced by late spring frost kill, most notably in species like gambel oak (Quercus gambelii) (Wilson et al. 1976), or by heat desiccation following surface burning (Pearce 2007). The implications of
applying the aforementioned models to appraising fire behaviour potential in such fuel complexes are unknown.

The purpose of this paper is to ascertain the relative magnitude of a foliar moisture effect on the horizontal spread rate of crowning conifer forest and shrubland fires based on a critical examination of the existing and pertinent literature. This includes (i) laboratory experiments from the needle to small tree scales, (ii) experimental fire field studies and (iii) model functions of theoretical and empirical origin. Both live and dead canopy foliage are considered.

**Laboratory evidence for a foliar moisture effect on crown fire rate of spread**

Chandler *et al.* (1983, pp. 33–34) observed that ‘There has been little formal research on the relationship between foliage moisture and fire behaviour, primarily because such experiments involve the deliberate initiation of crown fires in living fuels. To explore the full range of variables would be both expensive and dangerous’. As a result, much of our current understanding of the effect of live fuel moisture on fire behaviour comes from laboratory scale experiments looking at vegetation flammability metrics (White and Zipperer 2010).

These laboratory studies, involving foliage samples and small ‘Christmas trees’, have demonstrated that foliar moisture has a profound effect on various aspects of flammability. Although these studies do not specifically look to examine the direct effects of FMC on horizontal crown fire ROS and thus it is questionable whether the results are directly transferable to the field, they nevertheless provide insight, although there are limitations.

**Needle and foliage scale laboratory experiments**

Several studies have attempted to characterise the relative flammability of fuel particles and its relationship to live fuel moisture through bench scale experiments in which fuel samples are subjected to a fixed heat flux and in turn metrics such as time to ignition, flame size and duration are quantified (e.g. Dickinson and Kirkpatrick 1985; Mak 1988; Dimitrakopoulos and Papaioannou 2001; Etlinger and Beall 2004; Dimitrakopoulos and Papaioannou 2001; White and Zipperer 2010) for an excellent review of bench scale flammability test types. In most of these experiments the moisture content of live fuels has been found to have a significant effect on time to ignition and flame characteristics (e.g. Bunting *et al.* 1983; Xanthopoulos and Wakimoto 1993; Dimitrakopoulos and Papaioannou 2001; Etlinger and Beall 2004; Pausas *et al.* 2012). Nonetheless, the extrapolation of these results to real-world situations is considered questionable given that such laboratory flammability studies seldom succeed in realistically replicating the heat transfer mechanisms and combustion processes driving wildland fire propagation (Fernandes and Cruz 2012).

Weise *et al.* (2005) used a cone calorimeter (Babrauskas 1984) with a radiosity of 25 kW m⁻² (out of a possible 100 kW m⁻²) imposing a constant radiant flux onto the fuel samples of 18.25 kW m⁻² (emissivity × view factor = 0.73 as per Babrauskas 2003). Pausas *et al.* (2012) submitted gorse (*Ulex parviflorus*) samples to a radiant flux of 4.6 kW m⁻² from a quartz epiradiator. These radiative heat flux values are much lower than observed in moderate-intensity shrubland fires where peak radiative heat fluxes between 36 and 150 kW m⁻² have been measured (Silvani and Morandini 2009; Cruz *et al.* 2011).

Peak radiative heat fluxes of 250–300 kW m⁻² have been measured in crown fires in conifer forests (Butler *et al.* 2004a; Frankman *et al.* 2012).

Convective heat transfer is also not well represented in the laboratory experiments carried out to date; in cone calorimeter based experiments (Dimitrakopoulos and Papaioannou 2001; Weise *et al.* 2005a), convection heat transfer is negligible (Babrauskas 1984). In epiradiator-based experiments where the heat source is positioned below the fuel particle, convection can act as a cooling mechanism. In the experimental setup of Pausas *et al.* (2012), convection acted as a cooling mechanism after the fuel particle temperature surpassed ~150°C. Conversely, the Xanthopoulos and Wakimoto (1993) experiments were based solely on convective heat transfer from a non-forced hot air column with temperatures varying between 400 and 640°C. Convective heat fluxes were not calculated in these experiments but average effective heat transfer coefficients given in Xanthopoulos (1990) suggest values between 7.3 and 11.5 kW m⁻². These values are much lower than the measurements of 40 and 61 kW m⁻² made by Silvani and Morandini (2009) in moderate-intensity, wind-driven shrubland fires. Similarly, convective heat fluxes peaking at 150 kW m⁻² were measured in high-intensity crown fires (Butler 2010).

Measured peak convective and radiative heat fluxes in free-burning fires coincide with the arrival of the ignition interface to the measuring sensors (Butler *et al.* 2004a; Silvani and Morandini 2009; Butler 2010), implying that unburned fuel particles are subjected to these very high heat fluxes immediately before and at the time of ignition (Butler 2010). Heating rates determine the rate, pathways and efficiency of pyrolysis of woody and non-woody plant materials (Shafizadeh 1968; Sussott 1980). As such, the low heating rates (up to two orders of magnitude lower) obtained in some laboratory experiments might limit the extrapolation of these data to free-spreading outdoor fires. Weise *et al.* (2005a) noticed that differences in time to ignition for different species and fuel moisture contents tended to decrease when cone calorimeter heat fluxes were set higher than 25 kW m⁻², implying that at heat fluxes representative of high-intensity fires the effect of moisture would be small. White and Zipperer (2010) also note that experiments with large heat sources will fail to detect differences between distinct fuel samples.

In order to explore the hypothesis that combustion behaviour of live vegetation is largely controlled by heat and mass transfer, Fletcher *et al.* (2007) conducted experiments on a flat flame burner (Engstrom *et al.* 2004) aimed at replicating the conditions of a flame front where leaf samples were exposed to heat fluxes ranging from 80 to 140 kW m⁻². Under these more realistic heating rates Fletcher *et al.* (2007) did not find an effect of fuel moisture content on time to ignition. Experiments by Pickett *et al.* (2010) with the same experimental apparatus showed that in green leaf samples moisture remains in the leaf after ignition occurs. This suggests that the release of pyrolysates from the leaf surface and their subsequent gas phase combustion do not require the removal of moisture located in the internal tissues of the leaf. This is in contrast to the commonly held modelling assumption that all moisture is evaporated from the fuel particle.
before ignition occurs (Van Wagner 1977; de Mestre et al. 1989; Mell et al. 2009). These results suggest that the effect of moisture content might be made inconsequential under the high convective and radiative heat fluxes characteristic of high-intensity crown fires.

**Laboratory experiments with small conifer trees**

Several studies have been conducted in the laboratory using small, individual conifer trees that have quite dramatically shown an influence of FMC on various aspects of forest fuel flammability. This work has been conducted in a variety of settings by different organisations over the years, initially by forest fire researchers in Canada investigating Christmas trees as a fire hazard (Van Wagner 1962), then the Christmas tree industry itself (see summary by Koelling 1998), followed by structural or urban fire researchers (e.g. Madrzykowski 2008). More recently this type of experimental test fire approach has been used in connection with the investigation of fire dynamics related to the wildland–urban interface (Baker 2011).

Van Wagner (1967a) carried out flammability tests with small specimens (1.5 m tall) of three conifer tree species: balsam fir (Abies balsamea), Scots pine (Pinus sylvestris), and white spruce (Picea glauca). The two measures of flammability selected for analysis included the proportion of crown fuel consumed and the weight of foliage consumed per ignition. It was determined that Scots pine and balsam fir could be ignited with a single match at respective FMC thresholds of ~65 and 50%. At a FMC of less than 20% all three species were found to be very flammable and would ‘burn with great violence'; similarly, Damant and Nurbakhsh (1994) demonstrated that was found to depend significantly on FMC.

Van Wagner (1967b) conducted a further laboratory experiment to demonstrate that the flammability of a single conifer species with FMC levels more typical of living trees found under field conditions. Several similar 1.5-m-tall white spruce trees were locally harvested, brought inside, and treated to obtain a FMC range of 68 to 124% by placing the butts of some in water and allowing others to dry for varying periods. The trees were burned inside a flame or smoke hood by igniting balls of crushed newspaper as a fuel for producing the heat source. As Van Wagner (1967a) was to point out, ‘Crowning forest fires, of course, bear witness to this [same] limitation’.

Van Wagner (1967b) concluded that FMC within the range observed had ‘a marked effect on the flammability of single trees’ as indicated by the ~30-fold increase in thermal radiation.

Quintilio (1977) similarly preconditioned 1 m-tall lodgepole pine (Pinus contorta) trees to FMC values between 70 and 120% in order to examine the possible increase in crown foliage flammability associated with the ‘spring dip’ phenomenon or seasonal minimum observed in FMC in the spring (Van Wagner 1974). Trees were anchored to a weight loss recording platform in order to examine the effect of FMC on needle weight loss during active flaming combustion. Burning of the sample trees was accomplished by igniting 5.0 g of air-dry excelsior that had been placed around the base of each stem. Quintilio (1977) found that this measure of flammability varied considerably over the range in FMC examined. Sample trees with low FMC lost weight at four times the rate of those with high FMC.

Several Christmas tree experimental fire studies have been undertaken by the Fire Research Division of the US National Institute of Standards and Technology (NIST). Several tree species were investigated including Scots pine, Fraser fir (A. fraseri) and Douglas-fir (Pseudotsuga menziesii). Tree heights ranged from ~1 to 4 m. The tests were conducted over a wide range in FMC (i.e. 2 to 154%). This work clearly demonstrated the dependence of heat of combustion (Babrauskas 2006) and the heat release rate/tree mass ratio (Baker and Woycheck 2007; Babrauskas 2008) on FMC for this specific experimental setup.

The most recent work undertaken by NIST is reported by Mell et al. (2009). They conducted a series of burning experiments using Douglas-fir trees ~2 and 5 m in height with the aim of gathering data to validate the predictive capacity of a physics-based numerical model. These experiments attempted to replicate a low-intensity surface fire under a tree. The authors pointed out that the relationship between FMC and the experiment’s burning characteristics was largely dependent on the ignition source. At the scale of these experiments, the burning behaviour was found to depend significantly on FMC.

The ignition source strength and FMC were the two main controls of combustion behaviour in the small, single conifer tree experiments. Nonetheless, the results regarding the FMC effect might not be directly transferable to assessing horizontal rate of fire spread in real-world crown fire situations. As discussed in the previous subsection on laboratory experiments, the effect of the much higher heat fluxes released by high intensity, free-burning crown fires results in distinct rates of pyrolysis and combustion dynamics.

**Field evidence for a foliar moisture effect on crown fire rate of spread**

As pointed out above, certain aspects of wildland fuel flammability can be demonstrated in the laboratory at the scale of a single shrub leaf or small individual conifer tree. However, of greater interest is the specific effect of FMC or live fuel moisture on the spread rate of a fire crowning in a conifer forest stand comprised of much taller trees or a shrubfield.

**Observations from outdoor experimental fires in conifer forests**

In addition to his studies of FMC as a factor in crown fire ignition, Van Wagner (1974) concluded, on the basis of physical logic, that FMC should also affect the ROS of crown fires. As empirical proof for a FMC effect on crown fire ROS, he presented data from two 0.19-ha sized (30.5 × 61 m) experimental fires, both carried out in a red pine (P. resinosa) plantation fuel complex under similar but not identical weather conditions (Van Wagner 1968). This information, represented in
Table 1. Summary of the burning conditions and associated fire behaviour characteristics for three experimental crown fires carried out in red pine plantation plots as described by Van Wagner (1964, 1968, 1977)
Adapted from Alexander (1998)

<table>
<thead>
<tr>
<th>Fire environment descriptor</th>
<th>Experimental fires</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1</td>
</tr>
<tr>
<td>Date of burning</td>
<td>8 June 1962</td>
</tr>
<tr>
<td>Ambient air temperature (°C)</td>
<td>24.4</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>26</td>
</tr>
<tr>
<td>10-m open wind speed (km h(^{-1}))</td>
<td>15</td>
</tr>
<tr>
<td>Litter moisture content (%)</td>
<td>10</td>
</tr>
<tr>
<td>Duff moisture content (%)</td>
<td>54</td>
</tr>
<tr>
<td>Foliar moisture content (%)</td>
<td>100</td>
</tr>
<tr>
<td>Forest floor consumption (kg m(^{-2}))</td>
<td>2.20</td>
</tr>
<tr>
<td>Rate of fire spread (m min(^{-1}))</td>
<td>10.8</td>
</tr>
<tr>
<td>Fireline intensity (kW m(^{-1}))</td>
<td>7300</td>
</tr>
<tr>
<td>Flame length (m)</td>
<td>15.0</td>
</tr>
<tr>
<td>Flame height (m)</td>
<td>14.8</td>
</tr>
<tr>
<td>Flame depth (m)</td>
<td>8.0</td>
</tr>
<tr>
<td>Flame front residence time (s)</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 1 in the form of experimental fires C6 and C4, indicates a 40% difference in FMC (i.e. 95 v. 135%). As Van Wagner (1974) notes, the difference in spread rate (27.4 v. 16.8 m min\(^{-1}\)) is ‘difficult to explain in any other way’.

This simple comparison by Van Wagner (1974) has been cited by others (e.g. Chandler et al. 1983) as a way of justifying a FMC effect on crown fire ROS. Closer examination of the burning conditions associated with these two experimental fires as summarised in Table 1 seems to support the notion of a significant effect of FMC on the spread of the two fires. However, as shown in Table 1, another experimental fire (R1) carried out in the same fuel complex at a FMC of 100% and exhibiting a spread rate of 10.8 m min\(^{-1}\) (Van Wagner 1964) does not fall in line with the other two experimental fire observations, as would be expected from the prevailing fuel and weather conditions (i.e. whereas the FMC is 5% higher for fire R1 compared with fire C6 and the 10-m open winds 4 km h\(^{-1}\) less, the litter moisture content is 2.0% less). Admittedly, the apparent discrepancies in the spread rates of the three experimental fires presented in Table 1 could simply reflect the natural variability in crown fire propagation (Taylor et al. 2004). Furthermore, the fairly small size of the plots in these experimental fires may preclude a representative estimate of the steady-state spread rate.

Van Wagner (1989, 1998) admitted that he could not find any secondary statistical effect that could be attributed to the FMC in the crown fire dataset used in the development of the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). Similarly, Cruz et al. (2005) through a reanalysis of the FBP database and other data from Australian exotic pine plantations found that FMC was not a significant predictor of crown fire ROS in conifer forest stands. In this dataset, FMC was not significantly correlated with the ROS of either active or passive crown fires, at least within the range of the dataset (75 to 135% for n = 37; Table 2).

Stocks et al. (2004) documented 10 experimental crown fires carried out in a jack pine (P. banksiana) – black spruce (Picea mariana) stand in Canada’s Northwest Territories at fairly low FMC levels (i.e. generally less than 90%). An analysis of variance was carried out modelling ROS against wind speed and FMC to examine whether the variability in FMC might explain any of the remaining variance in fire spread rate once the modelled effects of wind speed had been included. They found that FMC was not significant but did acknowledge that the FMC varied with a narrow range (~15%; Table 2).

It is possible that the effect on the phenomena under study is limited, and hence it is uncertain whether the lack of correlation between FMC and crown fire ROS is the result of the effect being masked by the high heat fluxes involved, a reflection of the empirical nature of the database, or both. The general difficulty of finding a distinct FMC effect in the experimental dataset is not unique. One faces the same general problem in conducting outdoor experimental fires in order to isolate a particular effect, in this case FMC. In contrast to the luxury often afforded by indoor laboratory fires, it is virtually impossible to hold everything constant while varying one parameter (Van Wagner 1971).

Observations from outdoor experimental fires in shrublands
Most spreading shrubland fires can be technically considered crown fires, as the main fire-carrying fuel layer has a well developed vertical dimension and live fuels are typically the bulk of the fuel consumed in flaming combustion (Rothermel 1972). Several field-based experimental burning programs carried out over the last 40 years in an effort to quantify the effect of environment variables on rate of fire spread in shrubland fuel complexes. To our knowledge not a single published scientific study has reported a statistically significant correlation between the moisture content in live shrubland fuels and rate of fire spread (Table 2). Other than the Lindenmuth and Davis (1973) and Vega et al. (1996) studies, none of the statistically based models developed from these datasets explicitly included live fuel moisture as a variable in their models. The model of Vega et al. (1996) indicated that rate of fire spread increased with an increase in moisture, illustrating one of the drawbacks of relying entirely on statistical analysis. It is worth noting that the shrubland studies listed in Table 2 deal only with rate of fire spread. The process of sustained fire propagation in shrubland fuels such as dealt with by Weise et al. (2005b) for example is not considered here.

One of the confounding problems in elucidating a live fuel moisture effect in shrublands is the degree of variation in the live : dead ratio even within a given species (Buck 1951; Paysen and Cohen 1990). This is in contrast to conifer forests where the amount of dead material is generally low, unless the stand has been killed as a result of insect attack or disease in which case all of the foliage is viewed as dead.

Comparison of foliar moisture functions for adjusting crown fire rate of spread
In order to gauge the relative magnitude of a FMC effect on crown fire ROS, a comparison was undertaken of five related
Table 2. Summary of field studies involving crown fire behaviour in conifer forests and shrubland fire behaviour with respect to the statistical significance (\( P \)) between live fuel or foliar moisture content (FMC) and rate of spread (ROS)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Dominant species and principal location</th>
<th>Number of fires</th>
<th>Nominal fuel height (m)</th>
<th>Range in FMC (%)</th>
<th>Range in ROS ( (\text{m min}^{-1}) )</th>
<th>Correlation coefficient (( P ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conifer forests</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stocks et al. (2004)</td>
<td>Jack pine–black spruce (Northwest Territories, Canada)</td>
<td>10</td>
<td>10.1</td>
<td>79–89</td>
<td>15–70</td>
<td>0.04 (0.99)</td>
</tr>
<tr>
<td>Cruz et al. (2005) passive crown fires</td>
<td>( P )inus spp. and ( P )icea spp. (Canada)</td>
<td>13</td>
<td>4.1–19</td>
<td>75–118</td>
<td>3.4–15.4</td>
<td>0.120 (0.05)</td>
</tr>
<tr>
<td>Cruz et al. (2005) active crown fires</td>
<td>( P )inus spp. and ( P )icea spp. (Canada)</td>
<td>24</td>
<td>2.9–14</td>
<td>78–135</td>
<td>7.5–51.4</td>
<td>−0.350 (0.05)</td>
</tr>
<tr>
<td>Shrublands</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thomas (1970)</td>
<td>( C )allina vulgaris (UK)</td>
<td>12</td>
<td>0.5</td>
<td>10–60</td>
<td>1.1–18</td>
<td>( - )A</td>
</tr>
<tr>
<td>Lindenmuth and Davis (1973)</td>
<td>( Q )uerus ( t )urbinella (Arizona, US)</td>
<td>32</td>
<td>0.9</td>
<td>71–142</td>
<td>up to 14</td>
<td>0.08 (&gt;0.05)B</td>
</tr>
</tbody>
</table>
| van Wilgen et al. (1985)   | \( L \)euca
dendron \( k \)aerolus (South Africa)                        | 14              | 1.8                     | 58–147           | 2.4–53                               | −0.30 (0.29)                    |
| Marsden-Smedley and Catchpole (1995) | \( G \)ynmoscoenus \( s \)phaerocephalus (Tasmania, Australia) | 68              | 0.3                     | 23–132           | 0.6–55                               | 0.06 (0.69)                     |
| McCaw et al. (1995)        | \( E \)ucalyptus \( t \)etragon\( a \) (Western Australia, Australia) | 9               | 2                       | 68–90            | 7.7–40.5                             | −0.17 (0.66)                    |
| Catchpole et al. (1998)     | Heath and mallee (New Zealand and Australia)                         | 133             | 0.2–4.8                 | 68–235C          | 0.6–60.0                             | \( - \)D (>0.05)B               |
| Fernandes et al. (2000)    | \( E \)rica \( u \)mbellata, \( C \)hamamaesp\( a \)rium \( t \)ridentatum \( P \)ortugal) | 44              | 0.5                     | 66–112           | 0.7–14.1                             | 0.26 (>0.05)B                   |
| Fernandes (2001)           | \( U \)lex \( s \)p., \( E \)rica \( s \)p., \( C \)hamamaesp\( a \)rium \( t \)ridentatum \( P \)ortugal) | 29              | 0.7                     | 72–113           | 0.7–20.0                             | \( - \)D (>0.05)B               |
| Biglili and Saglam (2003)   | \( Q \)uerus \( c \)occifer\( a \), \( A \)rhus \( a \)ndrachne (Turkey) | 25              | 0.5                     | 28–51            | 0.8–6.6                              | 0.36 (0.075)                    |
| Saglam et al. (2007)       | \( Q \)uerus \( c \)occifer (Turkey)                                  | 17              | 1.3                     | 69–109           | 0.6–8.4                              | −0.42 (0.09)                    |
| Saglam et al. (2008)       | \( A \)rhus \( a \)ndrachne, \( P \)istacia \( l \)ent\( a \)c\( s \) (Turkey) | 18              | 2.3                     | 60–164           | 0.4–7.4                              | 0.36 (0.138)                    |
| Davies et al. (2009)       | \( C \)allina \( v \)ulgaris, \( V \)accinium \( m \)yril\( i \)us (UK) | 26              | 0.3                     | 55–97            | 0.5–12.6                             | \( - \)B                       |
| Cruz et al. (2010)         | \( E \)ucalyptus \( c \)alicog\( o \)na, \( E \) diversif\( o \)lia           | 28              | 1.3–4.5                 | 51–93            | 1.2–55                               | 0.17 (0.39)                     |
| Cruz et al. (2012)         | \( E \)ucalyptus \( c \)alicog\( o \)na, \( E \) diversif\( o \)lia, \( E \) tetragona       | 37              | 1.7–4.5                 | 51–93            | 1.2–55                               | 0.13 (0.61)                     |

\(^A\)The correlation coefficient and its significance were not given although the author did note that contrary to expectation there was a positive relationship between rate of fire spread and live fuel moisture content.

\(^B\)Exact \( P \) value not given.

\(^C\)W. R. Anderson, University of New South Wales, pers. comm., 2012.

\(^D\)Correlation coefficient not given.

\(^E\)The correlation coefficient and its significance were not given although the authors did mention that live fuel moisture did not play a major role in determining the resulting behaviour of the experimental fires.
functions, both theoretical and empirically based. Functions based on a weighted or composite live and dead fuel moisture content value such as that of Trabaud (1979) were not considered. The five selected functions are briefly reviewed here in the interest of completeness.

**Van Wagner’s foliar moisture effect**

Van Wagner (1974) acknowledged that there is essentially no specific crown fire theory in the literature that accounts for the seasonal variation in FMC on the ROS of crown fires (and this remains the case). He therefore devised an approach based on a commonly used principle formulated by Thomas et al. (1964) that the forward ROS $R$ should be (i) proportional to the horizontal heat flux $E$ through the crown layer, (ii) inversely proportional to the foliar ignition energy $h$ and (iii) inversely proportional to the fuel bulk density $d$. This can be expressed in simple mathematical terms as follows:

$$ R \propto \frac{E}{hd} \quad (1) $$

In considering the first effect, it was assumed that $E$ was mainly a function of radiation. From Boltzmann’s fourth-power law of thermal radiation we have the following relationship:

$$ E = c(T/1000)^4 \quad (2) $$

where $c$ is assumed to be equal to 1000 and $T$ is absolute temperature (K). Van Wagner (1974) considered a baseline crown fire flame radiometric temperature of 1500 K assuming oven-dry fuel and an air supply twice the minimum stoichiometric requirement (Van Wagner 1963). Considering the effect of moisture in reducing flame temperature he proposed (Van Wagner 1974):

$$ T = 1500 - 2.75 \text{ FMC} \quad (3) $$

Combining Eqns 2 and 3 gives us the following expression for the effect of FMC on the flame’s radiation intensity:

$$ E = 1000(1.5 - 0.00275 \text{ FMC})^4 \quad (4) $$

As for the second effect, the energy $h$ required to preheat fuel to ignition can be stated as a simple function of FMC (Van Wagner 1977, 1989):

$$ h = 460 + 25.9 \text{ FMC} \quad (5) $$

The specific details of the derivation of Eqn 5 are given in Van Wagner (1967b, 1968).

The third effect was omitted by Van Wagner (1989) on the grounds of simplification, thereby leaving the first two effects to be used in developing a factor to account for the FMC effect on crown fire ROS. Based on Eqns 4 and 5, we can now express the foliar moisture effect (FME) function as follows:

$$ \text{FME} = 1000(1.5 - 0.00275 \text{ FMC})^4/(460 + 25.9 \text{ FMC}) \quad (6) $$

In practice, the FME is used in a relative sense, being normalised against some standard FMC value, termed the FMEo:

$$ \text{CFS} = \frac{\text{FME}}{\text{FMEo}} \quad (7) $$

where CFS is the relative crown fire spread factor. This value is in turn used to adjust a predicted crown fire ROS for a given FMC relative to FMEo. CFS equals 1.0 at the reference FMC value used in Eqn 7 to derive FMEo.

In the C-6 (conifer plantation) fuel type of the FBP System, FMEo was deemed to be 0.778 given a reference FMC of 97%, reflecting the average value in the crown fire dataset used in the development of the FBP System (Van Wagner 1989). Thus, given a range in FMC of 85 to 120%, the CFS would in turn vary from 1.24 to 0.68. In a later work, Van Wagner (1993) assumed a FMEo of 1.365 based on an average FMC of 67% for the set of experimental fires carried out in immature jack pine by Stocks (1987b).

Van Wagner’s (1989) FME function was also an option in the first version of the NEXUS fire behaviour modelling system (Scott and Reinhardt 2001), although this effect in assessing crown fire behaviour potential has to our knowledge not been used in any simulation study published to date, other than in the sensitivity analysis undertaken by Scott (1998). Scott and Reinhardt (2001) suggested using an ‘overall average FMC among all species during the fire season in the Northern Rocky Mountains’ and suggested that a FMC of 100% might be such a value (Scott 1998). The FME function was removed from later versions of NEXUS based on the reasoning that the wildfires used in the formulation of the Rothermel (1991) crown fire ROS model occurred under dry summertime conditions and inherently were characterised by low, but unknown, FMC values (J. H. Scott, Pyrologix Wildland Fire Science, pers. comm., 2011). It is worth noting that Scott and Reinhardt (2001) inadvertently omitted the 1000 constant in the numerator of Eqn 6 when writing Eqn 7 of their review of the FME computation. As a result, they state that FMEo equals 0.0007383 for a FMC of 100%, when in fact it should have been 0.7383 in order to be compatible with the works of Van Wagner (1989, 1993, 1998).

**Albini (1996) physics-based crown fire rate of spread model**

Albini (1996) extended his two-dimensional physics based model (Albini 1985, 1986; Albini and Stocks 1986) to describe the ROS of a crown fire and the shape of its ignition interface. In his numerical model, Albini (1996) assumes radiative heating from the fuel bed and free flame above it as the dominant heat transfer mechanism. He further assumes that fuel heating is caused by a gain of internal energy in fuel particles due to an increase in temperature. The relationship between the net heat absorbed and the fuel temperature is discontinuous due to the fuel moisture content. As such, the effect of FMC is incorporated into a three step heating model that takes into account the latent ($L$) and specific heat of the water ($c_w$) present in the fuel. The rise in fuel temperature ($dT$) as a function of net heat absorbed ($dQ$) is given by (Albini 1985; de Mestre et al. 1989):

$$ dQ = \begin{cases} (c_p + M \cdot c_w)dT, & T < 373K \\ -LdM, & T = 373K \\ c_pdT, & 373K > T > T_{ig} \end{cases} \quad (8) $$
where $c_p$ is the specific heat of dry fuel and $M$ is an intrinsic fuel layer moisture content weighted from fuel load, moisture and consumption (see Albin and Stocks 1996 for computational details).

Albin’s (1996) model closure required the estimation of two semi-empirical parameters that describe the radiation intensity from the burning zone and the free flame. Measurements of flame radiosity in experimental crown fires (Butler et al. 2004; Stocks et al. 2004) and further refinements (Call and Albin 1997) led to formulation of Albin’s (1996) model as a fully predictive model as presented in Butler et al. (2004b). As Butler et al. (2004b) note, the Albin (1996) function presented in fig. 3 of their paper ‘clearly indicates that fire spread rate decreases monotonically with increasing live fuel moisture content. This behaviour matches observed behaviour in the qualitative sense; unfortunately, the paucity of detailed field data prevents a quantitative comparison between predicted and measured response to live fuel moisture content’.

For the purposes of examining the FMC function in the Albin (1996) model, we relied on data plotted in Albin (2000). A FMC of 100% was set as a reference level on the basis of previous precedent set by Albin and Stocks (1986) and subsequently used by Butler et al. (2004b).

Lindemuth and Davis’ (1973) Arizona oak chaparral rate of fire spread model

Lindemuth and Davis (1973) developed a statistical or empirically based model for predicting the head fire ROS in oak chaparral (predominately Quercus turbinella) shrublands in Arizona. The model required six inputs, including FMC, and was developed with data from 32 outdoor experimental fires conducted over several seasons; the highest observed spread rate was 14 m min$^{-1}$. The model accounted for 81% of the variation in the observed rate of fire spread. The FMC for the experimental fires averaged 84.4% and ranged from 71.4 to 142.4%. The relative effect of FMC on fire spread rate in the Arizona oak chaparral fuel type was deduced by taking the ratio of predicted rate of fire spread for a given FMC level to the predicted ROS based on the average effects of the other input variables – air temperature, relative humidity, net solar radiation, 6.1-m open wind speed and foliar phosphorus content.

Rothermel (1972) surface fire model

In the Rothermel (1972) surface fire ROS model that is imbedded within the BehavePlus fire modelling system (Andrews et al. 2008), live fuel moisture has a damping effect on the rate of fire spread. This effect is calculated through the moisture damping coefficient ($\eta_{Mlive}$) taking into account the live fuel moisture content ($M_{live}$) and the live fuel moisture of extinction ($M_{Xlive}$): $\eta_{Mlive} = 1 - 2.59 \cdot \left( \frac{M_{live}}{M_{Xlive}} \right) + 5.11 \cdot \left( \frac{M_{live}}{M_{Xlive}} \right)^2 - 3.52 \cdot \left( \frac{M_{live}}{M_{Xlive}} \right)^3$ (9)

The moisture of extinction of live fuels is a dynamic quantity formulated as a function of the ratio of live to dead fuel load ($z$) and dead fuel moisture content ($M_{dead}$) (Fosberg and Schroeder 1971):

$$M_{Xlive} = 2.9 \cdot \left( \frac{1 - 2^z}{z} \right) \cdot (1 - 3.33 \cdot M_{dead}) - 0.226 \quad (10)$$

Implicit in this relationship is the assumption that the energy required for the ignition of live fuels comes from dead fuels (Jolly 2007). As such, fire beds made up exclusively of live fuels do not carry fire, a state not consistent with empirical evidence (Cohen and Brashaw 1986). For fire behaviour fuel model 4 – chaparral (Anderson 1982), the moisture of extinction of live fuels varies between 52 and 373% for respective dead fuel moisture content between 20 and 3%. The moisture damping coefficient is used to calculate the energy released from the combustion of live fuels (Rothermel 1972); this latter quantity is then incorporated in a heat balance formulation to determine the rate of fire spread.

Catchpole and Catchpole (1991) refined Rothermel’s (1972) early work by extending Wilson’s (1990) exponential moisture damping term and probability of extinction function (instead of moisture of extinction) to fuel complexes with a mixture of live and dead fine fuel particles. Their formulation improved the performance of Rothermel’s (1972) model when tested against the rate of fire spread data from van Wilgen et al. (1985) for South African fynbos shrublands. A reformulation of the Rothermel (1972) model by Sandberg et al. (2007) did not alter the original moisture damping coefficient depicted in Eqs 9 and 10.

We selected a reference level of 75% for the purposes of assessing the relative effect of live fuel moisture in a chaparral fuel complex using the BehavePlus fire modelling system. This value was selected on the basis of seasonal trends presented in various sources (e.g. Rothermel and Philpot 1973; Weise et al. 1998, 2005b). Chandler et al. (1983, p. 35) have noted that ‘In Mediterranean shrub communities fires burn intensely when foliage moisture drops below 75 percent’. Dennison and Moritz (2009) found, for example, that a live fuel moisture level of 79% represented a critical threshold for large fire growth in chaparral.

Fuel Characteristic Classification System crown fire rate of spread model

Schaaf et al. (2007) proposed a crown fire ROS model designed to be used within the Fuel Characteristic Classification System (Sandberg et al. 2007). Schaaf et al. (2007) proposed a foliar moisture damping term ($\eta_{FMC}$) that approximates the effect incorporated in Van Wagner’s (1977) heat of ignition relationship represented by Eqn 5:

$$\eta_{FMC} = \left[ \frac{FMC_{ref} \cdot M_{dead}}{\text{max}(FMC_{ref}, FMC)} \right]^{0.61} \quad (11)$$

where $FMC_{ref}$ is a FMC reference minimum at maximum foliar flammability, set at 75%. Schaaf et al. (2007) state that $\eta_{FMC}$ is a constant equal to unity below an FMC of 75%. Thus, the Schaaf et al. (2007) function explicitly indicates only a decrease in the effect of FMC on crown fire ROS, never an increase. The application of Eqn 11 follows the general modeling approach
of Rothermel (1972) as described in the previous section. The damping coefficient is multiplied by the energy released by the combustion of the crown fuel layer to estimate the reaction intensity, which is then used to determine the crown fire ROS. Our analysis of the Schaaf et al. (2007) damping function assumes that an active crown fire dominates the propagation process.

Findings from comparison of existing functions for live canopy foliage

The FME function that is currently applied to predicting crown fire ROS in the C-6 (conifer plantation) fuel type of the FBP System (Forestry Canada Fire Danger Group 1992) as developed by Van Wagner (1989) is presented in Fig. 1a. The CFS is shown to vary from a value of 1.65 at a FMC of 70% to 0.68 for a FMC of 120%. Within this range, the Albini (1996) function is very similar to that of Van Wagner (1989). This is somewhat surprising in that although both functions have a similar theoretical basis their implementation in the models is quite different. In the Schaaf et al. (2007) function, FMC has a smaller effect than that proposed by Van Wagner (1989) and Albini (1996). The Schaaf et al. (2007) formulation has the lowest effect on rate of fire spread when we only consider the crown fire models. The effect of lower FMC values on ROS increases in all of the models except that of Schaaf et al. (2007) who chose to assume that regardless of the decrease in FMC below a 75% level, the relative effect remains a constant 1.0, although no supporting justification was given for this assumption.

Considering the shrubland models, the live fuel moisture function in the Lindenmuth and Davis (1973) rate of fire spread model for Arizona oak chaparral exhibits a rather shallow effect over a normal range of use (Fig. 1a). This is in stark contrast to the damping function exhibited by the Rothermel (1972) surface fire spread model when applied to the chaparral fuel model (Anderson 1982). Lindenmuth and Davis (1973) did not provide information on the significance of their live fuel moisture parameter. In their study, live fuel moisture was not correlated with ROS. It is therefore quite possible that they elected to include this parameter in their model on theoretical grounds even if its effect in the dataset was not statistically significant.

The Schaaf et al. (2007) formulation is seen to have a slope similar to that of Rothermel (1972) but they differ in their relative magnitude. Note again that the Schaaf et al. (2007) function results in a CFS = 1.0 for FMC values less than 75% (Fig. 1a).

In our comparison between distinct FMC functions embedded in fire behaviour models, we did not address any of the physics-based models that have been used to simulate wildland fire dynamics, such as FIRETEC (Linn et al. 2002) or WFDS (Mell et al. 2009). Attempting to elucidate the effect of FMC on rate of fire spread in a model such as FIRETEC, for example, is a complex task because of the coupling between heat transfer,
combustion and vapourisation embedded within the model. FIRETEC estimates the average fuel moisture content for each control volume taking into account the moisture contents of the individual live and dead fuels weighted according to their respective loads. The fuel moisture effect is accounted for through the water vapourisation rate. FIRETEC uses a probability density function for the fraction of initial moisture that has been evaporated or is being evaporated as a function of solid fuel temperature (Marino et al. 2012). The probability density function allows for a continuous process where moisture evaporation starts before the average fuel temperature reaches the boiling point of water and at high fuel moisture levels, a significant amount of moisture is still known to exist in the grid (fuel) cell when combustion occurs. The simultaneous occurrence of evaporation and combustion in a grid cell result from the respective probability density functions overlap at fairly low temperatures (400 K). There is no correspondence between these modelling results and the processes observed by Pickett et al. (2010) in green leaf samples where moisture was found to remain in the leaf following ignition (J.-L. Dupuy, INRA Unité de Recherches Forêtières Méditerranéennes, pers. comm., 2012).

Marino et al. (2012) used FIRETEC to conduct several simulation experiments to explore the effect of the weighted fuel moisture content on rate of fire spread in shrubland fuels. These authors found the average moisture content effect to follow an exponential decay function as observed in numerous empirical studies. Nonetheless, their results are not directly comparable with these empirical observations nor the foliar moisture effect functions as described in this paper. This is because the effect of moisture in FIRETEC is dynamic and varies with fuel complex characteristics (e.g. proportion of dead v. live fuels) and burning conditions, which in turn determine heat fluxes and combustion outcomes.

Extension of foliar moisture effect functions to dead canopy foliage

A broader range in FMC or live fuel moisture levels is portrayed in Fig. 1b compared with Fig. 1a. This enables one to readily gauge the consequences of applying any of the existing foliar moisture fire spread rate functions to dead or desiccated foliage. One can clearly see that the Lindenmuth and Davis (1973) and Schaaf et al. (2007) functions are fairly insensitive at very low FMC levels.

Conversely, the extrapolation of the Van Wagner (1989) and Rothermel (1972) functions to comparable levels suggest CFS values of ~8.0 at a FMC of 7% (Fig. 1b); the trend in the Albini (1996) curve implies an even higher CFS. This suggests for example that crown fires in stands retaining dead foliage should spread approximately eight times (or 800%) faster than those in healthy, green or live stands. Intuitively, this does not make sense as it would imply crown fire rates of spread of up to 800 m min⁻¹, which have never approached this value (Alexander and Cruz 2006). Nevertheless, Van Wagner (1989) FME function has been suggested for possible application to mountain pine beetle-attacked lodgepole pine stands (Moran and Cochrane 2012).

Is there any information available to suggest what the relative effect on crown fire ROS should approximately be at a FMC of 7%? The only published field study of fire behaviour in a standing dead conifer forest fuel complex for which ‘hard’ empirical data exist is that of Stocks (1987a) undertaken in spruce budworm (Choristoneura fumiferana)-killed balsam fir stands where an increase in arboreal lichens compensated for the needle defoliation. The study by Stocks (1987a) served as the basis for the dead balsam fir mixedwood – leafless fuel type (M-3) in the FBP System. The M-3 fuel type allows for variable quantities of dead balsam fir. Unfortunately, there is no true live, healthy balsam fir fuel type that presently exists in the FBP System. However, comparisons of active crown fire ROS in the M-3 fuel type with 100% dead fir to the mature jack or lodgepole pine fuel type (C-3) in the FBP System indicates that the difference would be something of the order of 3.6 times at the onset of the active crowning in the latter type and gradually decreasing to ~2.5 times (Fig. 2). Rate of spread observations gleaned from wild and prescribed fires in the ‘red’ stage of mountain pine beetle-attacked lodgepole pine forest stands in British Columbia suggests a difference of ~2.7 times (D. D. B. Perrakis, British Columbia Wildfire Management Branch, pers. comm., 2012).

Conclusions

Quantifying the effect of FMC or live fuel moisture on crown fire ROS in conifer forests and shrublands has so far proven to be a difficult endeavour. Laboratory-based studies where all variables but live moisture content are held constant suggest an effect of this variable on flammability metrics. Nonetheless, the fairly low heat fluxes of these experiments may limit the
extrapolation of these results to represent the dynamics characteristic of high-intensity crown fire propagation.

Although counterintuitive, examination of the available empirical evidence on FMC or live fuel moisture in relation to crown fire rate of spread in conifer forests and shrublands suggests, based on a 0.05 P value threshold, that there is no statistically significant relationship between these variables. This assertion applies within a FMC range of ~75–140% for conifer forest stands and a live fuel moisture range of ~60–140% for shrublands. It is possible that a small effect exists but the difficulty of controlling the environmental conditions in outdoor field experiments has so far precluded the quantification of this effect. It is worth noting that this analysis considers the ROS of an advancing crown fire and does not address the conditions necessary for crown fire ignition.

Five foliar or live moisture effect functions for adjusting crown fire ROS were examined. The empirical function of Lindenmuth and Davis (1973) and theoretical function of Rothermel (1972) for shrublands as well as the Schaaf et al. (2007) theoretical function for conifer forests indicate a distinct damping effect on rate of fire spread within a normal range of conditions. On the other hand, the two theoretical functions developed by Van Wagner (1989) and Albini (1996) both show strong effects below FMC reference levels.

None of the functions examined were admittedly ever intended to be applied to dry, dead canopy foliage and it is quite clear they would not be appropriate for such use. Accounting for the effects of critically low FMC levels on fire behaviour in certain fuel types, such as mountain pine beetle attacked stands, is a very real issue and need (Jenkins et al. 2012). Recent attempts to assess the effect of low FMC levels on crown fire ROS based entirely on conducting experimental fires in natural forest stands have met with mixed success (Schroeder and Mooney 2012).

Like most problems in applied wildland fire behaviour research, the most effective solution is a judicious mixture of physical theory, simulation modelling and experimentation (Van Wagner 1971) supplemented by experienced judgment and wildfire case study knowledge (Alexander 2007). Simulations that could be produced by the new generation of physics-based fire behaviour models such as FIRETEC and WFDS once they have been adequately evaluated (Alexander and Cruz, in press) is an encouraging possibility for helping to resolve the issue. Field experiments will need to be well designed from a statistical standpoint and undoubtedly novel in nature in order to avoid previous pitfalls when it comes to analysing the data for a FMC effect. For example, conducting experimental fires in coastal areas would allow one to take advantage of the uniformity in weather conditions associated with sea breezes (Stull 1988). Past efforts will no doubt provide relevant insights in this regard involving both artificial setups (e.g. Xanthopoulos 1990) as well as conventional experimental burning (Stocks 1987a, 1987b; Stocks et al. 2004).

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