Role of Foliar Moisture Content in the Silvicultural Management of Forest Fuels

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ABSTRACT: In combination with measured stand data and assumed environmental conditions, reasonable estimates of foliar moisture content (FMC) are necessary to determine and justify silvicultural targets for canopy fuels management strategies. FMC often is overlooked in fuels planning, with default values substituting for more precise estimates, but its role is operationally significant in the selection of silvicultural targets even at modest surface fire intensities. This article discusses the role of FMC in canopy ignition and summarizes the results of 11 studies on the FMC values and trends for 16 North American conifers. FMC values ranged from 73 to 480% but varied by species, foliage age, and season. The information presented here will be helpful to managers engaging in canopy fuels planning with the use of popular fire behavior and fuels management software (e.g., NEXUS, Fuels Management Analyst, and the Forest Vegetation Simulator’s Fire and Fuels Extension). West. J. Appl. For. 21(4):228–231.

Key Words: Stand structure, crown fire, wildfire hazard, canopy fuels.

The relationship of stand structure to fire behavior, and the basis for silviculturally modifying stands to reduce crown fire susceptibility, have been well established (Graham et al. 2004, Agee and Skinner 2005). In planning silvicultural treatments to achieve crown fire resistance, assumptions must be made about uncontrolled parameters that are beyond the scope of manipulation (Keyes and O’Hara 2002). One of these is the percent foliar moisture content (FMC) of overstory and midstory trees.

The quantitative basis for prescribing silvicultural treatments (such as thinning and pruning) to the aerial fuel complex is Van Wagner’s (1977) model of the relationships among crown fire initiation, surface fire intensity, and canopy fuel structure. Since its inception as a tool to predict the occurrence and behavior of crown fires, Van Wagner’s model has been refined and adapted in formats useful for fuels planning (Alexander 1988, Scott and Reinhardt 2001, Keyes and O’Hara 2002). It is used by virtually all decision-support software currently used in fuels planning in North America, including Farsite (Finney 1998), NEXUS (Scott 1999), the CrownMass program of the Fuels Management Analyst tool suite (Fire Program Solutions 2003), and the Fire and Fuels Extension to the Forest Vegetation Simulator (Reinhardt and Crookston 2003).

Using one or more fire behavior prediction programs, fuels planners identify structural targets that can reduce a stand’s susceptibility to crown fire initiation, crown fire spread, or both, and then propose fuels treatments to achieve these targets. Ideally, the effects of proposed silvicultural fuels treatments on fuel dynamics are considered also. For example, intensive thinning that reduces a stand’s canopy bulk density will diminish its potential for crown fire spread; however, it will increase the development of crown fire initiation potential by promoting vertical continuity in the aerial fuel complex because of the release of advance regeneration, the proliferation of stump sprouts and seedling regeneration, and the stalled recession of overstory tree crowns (Keyes and Varner 2006).

A target canopy base height (CBH) can be determined on the basis of anticipated surface fireline intensity (FLI) and the FMC of canopy fuels that will decrease susceptibility to torching or canopy ignition. Measured or modeled fuelbed properties are used in combination with fire weather scenarios to determine the FLI that is likely to occur, but fuels planners lack a standard basis for determining appropriate values for FMC. This article reviews relevant literature to address that need and discusses the importance of accurately specifying the FMC value assignment.

Relative Importance of FMC

The effect of FMC on canopy ignition relative to surface FLI is minor (Scott 1998), but it is significant enough to...
warrant attention in the fuels planning process. In Van Wagner’s (1977) canopy ignition equation (and, by association, all fuels planning software based on that equation), the canopy ignition height is much more sensitive to surface fire intensity than FMC. Because the importance of FMC is comparatively minor, the emphasis in fuels planning is on estimating the anticipated FLI (and on the fuels and environmental inputs associated with its prediction). Scott (2003), e.g., recommended using a fixed FMC value of 100%.

A locally explicit assessment of the sensitivity of canopy ignition to FMC can be estimated for stands with surface fuel loads of known or estimated quantities, distributions, and structures using a reformulation of Van Wagner’s canopy ignition equation (Equation 1):

\[ CBH_t = \frac{(FLI^{(1/1.5)})}{((0.010)(460 + 26 \times \text{FMC})}, \]  

(1)

where \( CBH_t \) (m) is the CBH above which canopy ignition is resisted \((\text{CBH}_t)\) for a stand’s anticipated surface \(\text{FLI} \) (kW/m) and percent FMC (Keyes and O’Hara 2002). Equation 1 is the same as that used by NEXUS (Scott 1999) to calculate “critical crown base height.” This CBH also can be determined from surface fire flame length, a more convenient measure of FLI, using Byram’s (1959) equation (Equation 2):

\[ FLI = 259 \times L^{17}, \]  

(2)

where \( L \) is surface fire flame length (m).

The effect of FMC on \( CBH_t \) is illustrated in Table 1 for surface fire flame lengths up to 5 m and FMC values of 70–150%. The FMC range encompasses values reported for mature foliage of 16 North American conifers (Table 2). At low surface fire flame lengths, differences in FMC have a minor effect on canopy ignition height. For example, where 1-m flame lengths are anticipated, the difference in \( CBH_t \) between FMC values of 90 and 130% is just 0.4 m. Hence, FMC has a relatively minor effect on the potential for transition of surface fire to crown fire under mild surface fire behavior conditions. An operational example of such a scenario exists in the case of thinning or pruning to prepare for silvicultural fuels treatments designed to resist torching and crowning during wildfire conditions. Roadside shaded fuelbreaks in high-traffic areas, where ignitions are frequent, represent one such application.

Understanding the effects of FMC on resistance to crown fire initiation is particularly important in even-aged stands that are poorly differentiated. By definition, trees in poorly differentiated stands have not segregated into crown classes that signify their divergent competitive positions. The intensively prepared and managed forest plantation, where homogeneity in spacing, microsite, and seedling stock type are maximized, represents an extreme case of this condition. In those types of stands, tree diameter, which is the most useful and common tree criterion in marking a stand for thinning, is a poor surrogate for CBH, and the usefulness of thinning to achieve a specified CBH is nil.

In these and similar circumstances, pruning is necessary to elevate the CBH. Pruning, which directly targets a specified residual \( CBH_t \), is a fairly precise tool for achieving a \( CBH_t \). More than any other available fuel management tool, pruning ensures that the stand’s posttreatment \( CBH_t \) is uniformly beyond the threshold for ignition. For these treatments, a species-specific FMC can be used to determine \( CBH_t \) values that are effective but also more operationally efficient than adopting a simple default FMC value (such as 100%). As \( CBH_t \) increases, pruning efficiency declines and cost rates grow. For example, a study of pruning efficiency in several western conifers showed that 3.4 trees could be pruned to 2.7 m for the same cost as pruning one tree to 5.4

### Table 1. Matrix of \( CBH_t \) (as defined by Equation 1 in meters) to resist canopy ignition for combinations of FMC and anticipated surface flame lengths.

<table>
<thead>
<tr>
<th>Flame length (m)</th>
<th>150</th>
<th>140</th>
<th>130</th>
<th>120</th>
<th>110</th>
<th>100</th>
<th>90</th>
<th>80</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.5</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>1.5</td>
<td>1.7</td>
<td>1.8</td>
<td>1.9</td>
<td>2.0</td>
<td>2.2</td>
<td>2.4</td>
<td>2.6</td>
<td>2.9</td>
<td>3.2</td>
</tr>
<tr>
<td>2.0</td>
<td>2.6</td>
<td>2.7</td>
<td>2.9</td>
<td>3.1</td>
<td>3.3</td>
<td>3.6</td>
<td>4.0</td>
<td>4.4</td>
<td>4.9</td>
</tr>
<tr>
<td>2.5</td>
<td>3.5</td>
<td>3.7</td>
<td>4.0</td>
<td>4.3</td>
<td>4.6</td>
<td>5.0</td>
<td>5.5</td>
<td>6.0</td>
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<tr>
<td>3.0</td>
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<td>5.2</td>
<td>5.6</td>
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<td>6.5</td>
<td>7.1</td>
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<td>3.5</td>
<td>5.7</td>
<td>6.1</td>
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<td>7.0</td>
<td>7.5</td>
<td>8.2</td>
<td>8.9</td>
<td>9.9</td>
<td>11.0</td>
</tr>
<tr>
<td>4.0</td>
<td>7.0</td>
<td>7.4</td>
<td>7.9</td>
<td>8.5</td>
<td>9.1</td>
<td>9.9</td>
<td>10.8</td>
<td>12.0</td>
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<td>11.7</td>
<td>12.6</td>
<td>13.7</td>
<td>15.0</td>
<td>16.5</td>
<td>18.4</td>
</tr>
</tbody>
</table>

The FMC value range encompasses the values reported for mature foliage of 16 North American conifers. FMC is comparatively unimportant at modest fire intensities (expressed here as flame length) but gains operational relevance when planning treatments to establish stand structures that resist crown fire initiation when fire behavior is more typical of late-summer wildfire conditions.
than its water content. For example, an analysis of young
Clausen 1965). This trend is physiologically based and is
steadily decline through summer to fall (Kozlowski and
crease to an annual maximum shortly thereafter, and then
during late spring (Philpot and Mutch 1971), rapidly in-

m (O’Hara et al. 1995). Thus, accurately determining the
height to which trees must be pruned to achieve a desired
level of resistance to crown fire initiation under specified
weather, climate, and surface fire behavior scenarios is
critical for maximizing treatment efficiency.

FMC Values and Trends

Fuels treatments are expected to be effective over a range
of temporally changing conditions; therefore, estimates of
FMC are best drawn from published studies that document
changes in FMC through seasons. Table 2 reveals a wide
range of moisture content values based on species, period of
measurement, and foliage age for 16 common North Amer-
ican conifers.

FMC varies seasonally. Lowest FMCs typically occur
during late spring (Philpot and Mutch 1971), rapidly in-
crease to an annual maximum shortly thereafter, and then
steadily decline through summer to fall (Kozlowski and
Clausen 1965). This trend is physiologically based and is
more a function of the leaf’s changing carbohydrate content
than its water content. For example, an analysis of young
red pine (Pinus resinosa) foliage revealed a seasonally
decreasing FMC even as the actual water content increased
(Kozlowski and Clausen 1965).

Like other fuel properties, the moisture content of foliage
also varies on a diurnal basis. Philpot’s (1965) study of
ponderosa pine (Pinus ponderosa) summertime FMC re-
vealed diurnal fluxes of 26–34%. FMC roughly tracked
ambient relative humidity measured during the same period.
More modest fluxes of 4–12% for ponderosa pine, Dou-

Table 2. Published percent FMC values for 16 North American conifers.

<table>
<thead>
<tr>
<th>Species</th>
<th>New foliage (^a)</th>
<th>Old foliage (^b)</th>
<th>Period (^c)</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
</table>

In some cases values are visually approximated to the nearest 5% from graphs.

\(^a\) Range of percent FMC values for 1st-year leaves.

\(^b\) Range of percent FMC values for 2nd-year leaves or older.

\(^c\) Month(s) comprising the study duration.

\(^d\) Two separate studies for each species in same publication.

The occurrence of worst-case fire weather and lowest
FMC usually are asynchronous. For conifers such as pon-
derosa pine and Douglas-fir, mature foliage FMC drops
below 100% but generally ranges between 100 and 130%
during the summer months when ignitions are most frequent
and fires most intense. In fuels planning, assumed FMC
values should be kept seasonally consistent with the fire
weather scenario used to predict surface FLI.

Foliage age is another primary determinant of variation in
FMC. Moisture content of 1-year leaves is typically higher
than older leaves by a substantial margin. For the species in
Table 2, the range of FMC values for new foliage is 120–480%
versus a range of 73–150% for older foliage (2nd
year or later). In a study of eastern white pine (Pinus strobus),
FMC values between July and September ranged from 130 to
140% for mature foliage but from 150 to 230% for new foliage
on the same trees (Kozlowski and Clausen 1965). Agee et al.
(2002) observed that tree crowns might experience partial
combustion that occurs primarily among older foliage of the
crown’s interior, without the concurrent combustion of new
foliage. For fuels planning purposes, therefore, it is suggested
that the FMC assignment be based on mature foliage (Table 2).

FMC Unknowns and Assumptions

Although studies have identified FMC differences in foli-
age age, none have established FMC differences in tree age.
Until this relationship is adequately studied, values in Table 2
should be applied regardless of stand or cohort age. No reports
have addressed FMC among stands of variable densities or
other attributes of stand structure. Therefore, fuels planners can not differentiate the effects of stand structure or treatments history on FMC and must rely on data that most closely represents their individual stand conditions.

Differences between species and regions are apparent (Table 2) but not with any obvious relationships to shade tolerance, latitude, or other useful ordinal characterizations that might suggest a need for regionally explicit FMC assignments or that would allow extrapolation to other species not represented in Table 2. As noted by Agee et al. (2002), however, the persistence of conifer foliage is positively associated with elevation and site quality. These associations may explain some of the differences that have been observed among species or between separate studies of the same species (Table 2).

The case of mixed-species stands introduces additional complexity. In stratified even-aged mixtures or mixed multi-cohort stands, it is most appropriate to use the FMC value of the species relegated to the lower-most stratum (the stratum that will initiate the canopy ignition process). For unstratified even-aged mixtures, where trees remain in a single strata rather than segregate into strata on the basis of species, it is suggested that the lowest FMC value be adopted among those species constituting at least 10% of the stand’s basal area.

Conclusions
Whenever possible, assumptions in silvicultural fuels management should be supported on the basis of best available scientific information. If the fire models used in fuels management are accepted as valid and are embraced as the quantitative basis for determining and justifying fuels treatment targets for individual stands, then it follows that precision in the assignment of parameter values is a desirable goal for customizing site-specific treatments that are both effective and efficient. This review shows that using one default FMC assignment in fuels planning ignores established differences among tree species and can unnecessarily exacerbate the intensity and cost of canopy fuels treatments (Table 1). Attention to these FMC differences is particularly important for thinning-based fuels treatments (Table 1). Differences between species and regions are apparent (2002), however, the persistence of conifer foliage is positively associated with elevation and site quality. These associations may explain some of the differences that have been observed among species or between separate studies of the same species (Table 2).

Literature Cited


