
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_t) 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

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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):

$$CBH_t = (FLI^{(1/1.5)}) / ((0.010)(460 + 26 * FMC)), \quad (1)$$

where CBH_t (m) is the CBH above which canopy ignition is resisted (CBH_t) for a stand's anticipated surface 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):

$$FLI = 259 * L^{2.17}, \quad (2)$$

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

long-unburned forests for prescribed burning. In such cases, the importance of the FMC assignment is minor.

At greater surface fire intensities and flame lengths, such as those associated with wildfire conditions, FMC gains operational relevance. At 2-m flame lengths, the difference in CBH_t between FMC values of 90 and 130% is 1.08 m (4.0 m for the former and 2.9 m for the latter). At 2.5-m flame lengths, the difference is 1.5 m (5.5 m versus 4.0 m). Differences in canopy ignition thresholds at these greater flame lengths are operationally significant and could have a substantial impact on silvicultural stand targets and treatment costs. Thus, accurately specifying FMC is important 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_t , and the usefulness of thinning to achieve a specified CBH_t is nil.

In these and similar circumstances, pruning is necessary to elevate the CBH_t . 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 fire flame lengths.

Flame length (m)	FMC (%)								
	150	140	130	120	110	100	90	80	70
0.5	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.6	0.7
1.0	0.9	1.0	1.1	1.1	1.2	1.3	1.5	1.6	1.8
1.5	1.7	1.8	1.9	2.0	2.2	2.4	2.6	2.9	3.2
2.0	2.6	2.7	2.9	3.1	3.3	3.6	4.0	4.4	4.9
2.5	3.5	3.7	4.0	4.3	4.6	5.0	5.5	6.0	6.7
3.0	4.6	4.9	5.2	5.6	6.0	6.5	7.1	7.9	8.8
3.5	5.7	6.1	6.5	7.0	7.5	8.2	8.9	9.9	11.0
4.0	7.0	7.4	7.9	8.5	9.1	9.9	10.8	12.0	13.3
4.5	8.3	8.8	9.4	10.1	10.8	11.8	12.9	14.2	15.8
5.0	9.6	10.2	10.9	11.7	12.6	13.7	15.0	16.5	18.4

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.

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

Species	New foliage ^a	Old foliage ^b	Period ^c	Location	Reference
<i>Abies balsamea</i> —balsam fir	180–230	130–150	July–Sept.	Wisconsin	Kozlowski and Clausen 1965
	130–220	110–150	July–Oct.	New Brunswick	Little 1970
	143–356	75–140	Jan.–Dec.	Alberta	Chrosiewicz 1986
<i>Abies grandis</i> —grand fir	167–313	112–138	June–Oct.	Washington	Agee et al. 2002 ^d
	140–309	112–151	June–Sept.	Washington	Agee et al. 2002 ^d
<i>Abies lasiocarpa</i> —subalpine fir	148–224	111–123	Aug.–Sept.	Washington	Agee et al. 2002 ^d
	120–315	—	June–Sept.	Washington	Agee et al. 2002 ^d
<i>Abies magnifica</i> —Shasta red fir	171–310	—	June–Sept.	Oregon	Agee et al. 2002
<i>Picea engelmannii</i> —Engelmann spruce	(mixed)	100–130	July–Oct.	New Mexico	Gary 1971
<i>Picea glauca</i> —white spruce	146–480	78–139	Jan.–Dec.	Alberta	Chrosiewicz 1986
<i>Picea mariana</i> —black spruce	131–349	73–126	Jan.–Dec.	Alberta	Chrosiewicz 1986
<i>Pinus banksiana</i> —jack pine	—	75–115	Jan.–Dec.	Ontario	Springer and Van Wagner 1984
	130–190	105–120	July–Oct.	Minn. & Mich.	Johnson 1966
	137–288	79–129	Jan.–Dec.	Alberta	Chrosiewicz 1986
<i>Pinus clausa</i> —sand pine	195–210	145–150	July–Oct.	Florida	Hough 1973
<i>Pinus contorta</i> —lodgepole pine	117–148	96–118	Late Aug.	Wyoming	Hartford and Rothermel 1991
<i>Pinus edulis</i> —pinyon pine	(mixed)	95–130	July–Oct.	Arizona	Jameson 1966
<i>Pinus ponderosa</i> —ponderosa pine	125–210	95–115	July–Oct.	Montana	Philpot and Mutch 1971
	149–275	85–120	June–Oct.	Washington	Agee et al. 2002 ^d
	135–338	86–137	June–Sept.	Washington	Agee et al. 2002 ^d
<i>Pinus resinosa</i> —red pine	160–250	120–140	July–Sept.	Wisconsin	Kozlowski and Clausen 1965
	135–200	110–130	July–Oct.	Minn. & Mich.	Johnson 1966
<i>Pinus strobus</i> —eastern white pine	150–230	130–140	July–Sept.	Wisconsin	Kozlowski and Clausen 1965
<i>Pseudotsuga menziesii</i> —Douglas-fir	120–200	80–120	July–Oct.	Montana	Philpot and Mutch 1971
<i>Tsuga canadensis</i> —eastern hemlock	170–280	120–150	July–Sept.	Wisconsin	Kozlowski and Clausen 1965

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.

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 American conifers.

FMC varies seasonally. Lowest FMCs typically occur during late spring (Philpot and Mutch 1971), rapidly increase 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 declining 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 revealed 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, Douglas-fir (*Pseudotsuga menziesii*), and grand fir (*Abies gran-*

dis) were observed during a late August day in Washington by Agee et al. (2002).

The occurrence of worst-case fire weather and lowest FMC usually are asynchronous. For conifers such as ponderosa 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 1st-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 foliage 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 management strategies in stratified mixed stands and for stands that require pruning to raise the CBH.

The values summarized in this article and their supporting documentation should be used in the fuels planning process and in justifying fuels treatments. Alexander (1988) lists several additional studies that are more obscure but that also could prove useful. For species lacking published FMC data, a low default value of 90 or 100% remains a prudently conservative assignment. In many cases, additional details that are present in the original research have been omitted from this discussion to present all species together in one comparative format (Table 2). Additional information beyond the values presented here is available from the primary literature and should be consulted and cited as necessary to establish the scientific basis for value assignments used in fuels planning.

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