Foliar Moisture Contents of North American Conifers

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Abstract*—Foliar moisture content (FMC) is a primary factor in the canopy ignition process as surface fire transitions to crown fire. In combination with measured stand data and assumed environmental conditions, reasonable estimates of foliar moisture content are necessary to determine and justify silvicultural targets for canopy fuels management strategies. FMC values reported in research publications are best used for this purpose. This paper summarizes the results of 11 studies on the FMC values and trends for 16 North American conifers. FMC values ranged from 73 to 480 percent but varied by species, foliage age, and season. FMC values presented here and the references associated with them 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).*

Keywords*: crown fire, fire surrogates, wildfire hazard, canopy ignition, shaded fuelbreak*

Introduction

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 behavior, surface fire behavior, and canopy fuel structure. Since its inception as a tool to predict the occurrence and behavior of crown fires, Van Wagner's model has since been refined and adapted in formats useful for fuels planning (Alexander 1988, Scott and Reinhardt 2001, Keyes and O'Hara 2002). It is currently utilized 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 Forest Vegetation Simulator's (FVS) Fire and Fuels Extension (Reinhardt and Crookston 2003).

Using one or more of those simulation 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 also considered (Keyes and Varner 2006). To decrease

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susceptibility to torching or canopy ignition, a target canopy base height is determined on the basis of anticipated surface fireline intensity and foliar moisture content. For the former parameter, measured surface fuelbed properties are utilized in combination with a worst-case fire weather scenario to determine the most intense surface fire behavior that is likely to occur. But fuels planners lack a standard basis for determining appropriate values for FMC. This paper reviews relevant literature to address that need.

Variability in Foliar Moisture Content

Fuels treatments are expected to be effective over a range of temporally changing conditions, so estimates of FMC are best drawn from published studies that document changes in foliar moisture content over seasons or years. A list of these is given in table 1 for 16 common North American conifer species. The table reveals a wide range of moisture content values based on species, period of measurement, and foliage age. These values are drawn from the primary literature; in some cases values have been visually approximated to the nearest 5 percent from published graphs.

Table 1—Published percent foliar moisture content (FMC) values for North America forest conifers. In some cases values are visually approximated to the nearest 5 percent from graphs.

Species	New foliage[1]	Old foliage[2]	Period[3]	Reference
Abies balsamea – balsam fir	180-230	130-150	Jul-Sep	Kozlowski and Clausen 1965
	130-220	110-150	Jul-Oc	Little 1970t
	143-356	75-140	Jan-Dec	Chrosciewicz 1986
Abies grandis – grand fir	167-313	112-138	Jun-Oct	Agee et al. 2002[4]
	140-310	110-150	Jun-Sep	Agee et al. 2002[4]
Abies lasiocarpa – subalpine fir	150-225	110-125	Aug-Sep	Agee et al. 2002[4]
	115-312	—	Jun-Sep	Agee et al. 2002[4]
Abies magnifica var. *shastensis* – Shasta red fir	170-310	—	Jun-Sep	Agee et al. 2002
Picea glauca – white spruce	146-480	78-139	Jan-Dec	Chrosciewicz 1986
Picea engelmanii – Engelmann spruce	(mixed	100-130)	Jul-Oct	Gary 1971
Picea mariana – black spruce	131-349	73-126	Jan-Dec	Chrosciewicz 1986
	—	75-115	Jan-Dec	Springer and Van Wagner 1984
Pinus banksiana – jack pine	130-190	105-120	Jul-Oct	Johnson 1966
	137-288	79-129	Jan-Dec	Chrosciewicz 1986
Pinus clausa – sand pine	195-210	145-150	Jul-Oct	Hough 1973
Pinus contorta – lodgepole pine	117-148	96-118	Late Aug	Hartford and Rothermel 1991
Pinus edulis – pinyon pine	(mixed	95-130)	Jul-Oct	Jameson 1966
Pinus ponderosa – ponderosa pine	125-210	95-115	Jul-Oct	Philpot and Mutch 1971
	149-275	85-120	Jun-Oct	Agee et al. 2002[4]
	115-340	85-135	Jun-Sep	Agee et al. 2002[4]
Pinus resinosa – red pine	160-250	120-140	Jul-Sep	Kozlowski and Clausen 1965
	135-200	110-130	Jul-Oct	Johnson 1966
Pinus strobus – eastern white pine	150-230	130-140	Jul-Sep	Kozlowski and Clausen 1965
Pseudotsuga menziesii – Douglas-fir	120-200	80-120	Jul-Oct	Philpot and Mutch 1971
Tsuga canadensis – eastern hemlock	170-280	120-150	Jul-Sep	Kozlowski and Clausen 1965

[1]Range of percent FMC values for first-year leaves.
[2]Range of percent FMC values for second-year leaves or older.
[3]Month(s) comprising the study duration.
[4]Two separate studies for each species in same publication.

Foliar moisture content varies seasonally. Lowest foliar moisture contents typically occurring during late spring (Philpot and Mutch 1971), rapidly increase to an annual maximum shortly therafter, 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 to 34 percent. FMC roughly tracked ambient relative humidity measured over the same period. More modest fluxes of 4 to 12 percent for ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), and grand fir (*Abies grandis*) were observed during a late August day in Washington by Agee et al. (2002).

The occurrence of worst-case fire weather and lowest foliar moisture content are usually asynchronous. For conifers such as ponderosa pine and Douglas-fir, old foliage FMC drops below 100 percent, but generally ranges between 100 percent and 130 percent 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 fireline intensity.

Foliage age is another primary determinant of variation in FMC. Moisture content of first-year leaves is typically higher than older leaves by a substantial margin. For the species in table 1, the range of FMC values for new foliage is 120 to 480 percent, versus a range of 73 to 150 percent 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 percent for old foliage, but ranged from 150 to 230 percent for new foliage on the same trees (Kozlowski and Clausen 1965). Although studies have identified FMC differences in foliage age, none have demonstrated FMC differences in tree age. Until this relationship is further examined, values in Table 1 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 must assume that stand structure or treatment history has no bearing on the FMC assumption. Differences between species and regions are apparent (table 1), but not with any obvious relationships to shade tolerance, latitude, or other useful ordinal characterizations that might suggest a need for regionally explicit assumptions, or that would allow extrapolation to other species not represented in table 1.

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 crown ignition process). For unstratified even-aged mixtures, it is suggested that the lowest FMC value be adopted among those species constituting at least 10 percent the stand's basal area.

Conclusion

Whenever possible, all assumptions in silvicultural fuels management should be supported on the basis of best available scientific information.

The foliar moisture content values summarized here should be utilized in the fuels planning process, and their supporting documentation cited in justifying silvicultural treatments of forest fuels. Alexander (1988) lists several additional studies of FMC that are more obscure but that could also prove useful. For species lacking published FMC data, a low default value of 90 or 100 percent is a prudently conservative assumption (e.g. Scott 2003). For this review, additional details that are present in the original research (table 1) were by necessity omitted in order to present all species together in one common tabular format. 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 assumptions used in fuels planning.

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