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Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior

James K. Agee[a,*], Clinton S. Wright[b], Nathan Williamson[c], Mark H. Huff[d]

[a]College of Forest Resources, University of Washington, P.O. Box 352100, Seattle, WA 98195, USA
[b]USDA Forest Service, Forestry Sciences Laboratory, 4043 Roosevelt Way, Seattle, WA 98105, USA
[c]Rocky Mountain National Park, 1000 Highway 36, Estes Park, CO 80517, USA
[d]USDA Forest Service, Pacific Northwest Region, 333 1st Avenue, Portland, OR 97208, USA

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Abstract

Foliar moisture was monitored for five conifers and associated understory vegetation in Pacific Northwest forests. Decline in foliar moisture of new foliage occurred over the dry season, while less variation was evident in older foliage. Late season foliar moisture ranged from 130 to 170%. In riparian–upland comparisons, largest differences were found for understory vegetation, with less variation evident for overstory trees. Minimum foliar moisture values of 100–120% are appropriate to use in crown fire risk assessment for the Pacific Northwest. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Foliar moisture; Pacific northwest; Wildland fire behavior; Crown fire

1. Introduction

Foliar moisture plays an important role in defining surface fire behavior in fuel types with a woody or herbaceous component, and in defining thresholds for crown fire initiation. The moisture content of shrubs and herbaceous vegetation will influence whether the fuels act as a heat source or a heat sink, either intensifying or lessening surface fire behavior (Burgan, 1979). Crown fire initiation, or torching, is a function of two poorly defined parameters: the height to the live crown and foliar moisture content (Van Wagner, 1977). Because a typical Pacific Northwest forest stand susceptible to torching is multilayered, defining a clear height at which the live crown begins is problematic (Wedin, 1999; Williamson, 1999), and foliar moisture content of most species, and its variation over the dry season, has not been widely assessed. Better understanding of the effect of green understory on surface fire behavior and the transition from surface fire to crown fire requires better information on foliar moisture content. We began to collect foliar moisture data as part of several projects across the Pacific Northwest to better characterize seasonal patterns of foliar moisture, and continued some collections over longer times to evaluate annual variability at a single site. All sites are subject to an annual dry season and collections were restricted to the period June–October at all sites.

Foliar moisture values used for crown fire risk assessment have varied from 75 to 130%, and seasonal trends occur in foliar moisture content (Alexander, 1988). He cites 17 studies across North America that provide foliar moisture data for at least one tree

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* Corresponding author. Tel.: +1-206-543-2688;
fax: +1-206-543-3254.
E-mail address: jagee@u.washington.edu (J.K. Agee).

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species, and concluded that foliar moisture content of 1-year-old needles changed throughout the year and was at a low point in the spring. The low moisture content of needles in the spring may contribute to early season crown fires in some forest types (e.g. Simard et al., 1983). As new needles develop that have higher moisture content, the average crown moisture content increases, and then decreases over the summer and fall (Lindemuth and Davis, 1970). Diurnal trends in foliar moisture have been documented (Philpot, 1965) and minima were found to occur between 12.00 and 16.00 h. Alexander (1988) speculated that diurnal fluctuations would not be significantly large enough to affect fire behavior predictions. In several forest types in the Pacific Northwest tree crowns include arboreal lichens as an additional component that may influence both crown fire risk and crown fire behavior, but little is known about their contributions in these areas.

The objectives of this study were to quantify trends in foliar moisture for several Pacific Northwest conifer and understory species and evaluate the influence of these trends on surface and crown fire behavior.

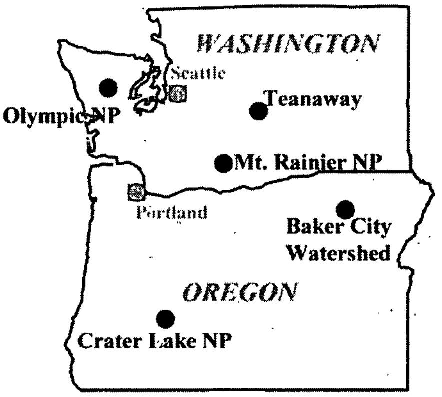

Fig. 1. Location of study sites in Oregon and Washington.

2. Methods

Foliar moisture was sampled at five locations (Fig. 1) at various times between 1986 and 2000. Dry season and annual precipitation varied considerably year by year (Table 1). Foliar moisture of subalpine fir (*Abies lasiocarpa*) was sampled at Olympic

Table 1
Climate during sample years near the five locations where foliar moisture was sampled[a]

Location and UTM	Calendar year	Dry season precipitation different from average[b]	Annual precipitation different from average[c]
11 436270E 4964989N			
Baker City	1998	+52 (11.9)	Wet (26.3)
10 660339E 5228641N			
Teanaway	1995	+29 (8.6)	Wet (56.5)
	1996	−11 (8.6)	Dry (56.5)
	1997	+24 (8.6)	Average (56.5)
	1998	+15 (8.6)	Average (56.5)
10 570606E 4749536N			
Crater Lake	1987	−3 (24.4)	Average (172.74)
10 596618E 5181987N			
Mount Rainier	1987	−17 (47.5)	Very dry (295.5)
10 4633865 5329834			
Olympic National Park	1986	−44 (11.0)	Average (65.4)
	1987	−13 (11.0)	Average (65.4)

[a] Dry season precipitation may show trends different from annual precipitation.

[b] Percent deviation that year from long-term (>50 years of record) May–September precipitation at nearest weather station. Actual precipitation at sample site may differ in absolute amount but trend should be similar to weather station. Average dry season precipitation (cm) in parentheses.

[c] Deviation from long-term (>50 years of record) average annual precipitation at nearest weather station. Very dry = >2 S.D. below average; dry = >1 S.D. below average; average = within 1 S.D. of average; wet = >1 S.D. above average. Average precipitation (cm) in parentheses.

National Park, Washington in 1986 and 1987, and at Mount Rainier National Park, Washington in 1987. Shasta red fir (*Abies magnifica* var. *shastensis*) was sampled in 1987 at Crater Lake National Park, Oregon. Six replicates of each species (approximately 30 g dry weight) were collected between 14.00 and 18.00 h on each sample date. Current year, older foliage, and small twigs (<0.5 cm) were separately sampled on the south side of the lower crown of sample trees.

In 1995 and 1996, in the Teanaway River Valley in the eastern Cascade Range of Washington, foliar moisture samples were collected regularly through the growing season from the following five species or groups of species: ponderosa pine (*Pinus ponderosa*) and grand fir (*Abies grandis*), new and older foliage separately; "grass" consisting of a grab sample of pinegrass (*Calamagrostis rubescens*), elk sedge (*Carex geyeri*) and other grass and grass-like plants; arboreal lichens as a group, including *Hypogymnia* spp., *Alectoria sarmentosa*, *Bryoria fuscescens*, *Letharia vulpina*, and other lichens; and "shrubs" as a group, including snowberry (*Symphoricarpos albus*), rose (*Rosa gymnocarpa*), huckleberries (*Vaccinium* spp.), birchleaf spirea (*Spiraea betulifolia*), ocean spray (*Holodiscus discolor*), snowbrush (*Ceanothus velutinus*) and serviceberry (*Amelanchier alnifolia*). The "grass" samples included live and dead standing biomass so that trends in curing during the season would be represented in the foliar moisture of the sample. Five replicates of each category were taken in the same area at regular intervals from June through September, between 12.00 and 16.00 h, and for trees from the lower crown on the south side of the tree. Most samples had about 30 g dry mass except for lichens where the average mass was closer to 10 g. In 1997 and 1998, only one early and one late season date was sampled using the same procedures. On 22 August 2000, sampling was conducted every 2 h from 10.00 to 16.00 h for ponderosa pine, grand fir, and Douglas-fir (*Pseudotsuga menziesii*), using duplicate samples.

Foliar moisture content was measured in the Baker City watershed of the Blue Mountains of northeastern Oregon, on 16 September 1998, using the same procedures as for the Teanaway in riparian and upland stands of the *P. menziesii*, *A. grandis*, and *A. lasiocarpa* forest series, representing an elevational sequence. Riparian samples were taken within 5 m of a perennial stream, and upland samples were taken 50 m upslope of the riparian zone. Overstory trees (a mixed sample of current and 1-year-old foliage), shrubs, and herbs were sampled with four replicates.

All samples were collected in airtight plastic bottles and returned to the laboratory. Samples were oven-dried in a minimum of 48 h at 70 °C. No further loss of mass was recorded from samples dried for longer periods. All moisture contents are expressed on a dry weight basis.

Sample size determinations were made to evaluate the precision needed to estimate foliar moisture 95% of the time within 10% of the mean. Late season samples for older foliage of grand fir and ponderosa pine in 1995–1998 were used to determine how many samples would be needed (Zar, 1996). Late season values were used because that is the time when wildfire risk is maximized in the Pacific Northwest.

3. Results

3.1. Subalpine fir and Shasta red fir

Current year foliage moisture content declined continually during the 1987 growing season (Fig. 2) for both species in upper montane to subalpine forest. By September, foliar moisture was 115–140% for subalpine fir, and about 170% for Shasta red fir. The previous year, when older foliage and small twigs of subalpine fir were also sampled (Fig. 3), the new foliage had minimum moisture content of about 150%. Little variation was seen in older foliage and small twig moisture content over the season, ranging between 100 and 120%.

3.2. Upland ponderosa pine, grand fir, and Douglas-fir

New foliage moisture content of ponderosa pine and grand fir declined continuously during the growing season of 1995 and 1996 to low values of about 130% (Fig. 4), while older foliage increased slightly in both years from about 80 to 90% in June to about 125% in September. A convergence in moisture content of new and old foliage occurs by the end of the dry season. Similar patterns for early and late season foliar moisture occurred in 1997 and 1998 (Table 2). Diurnal

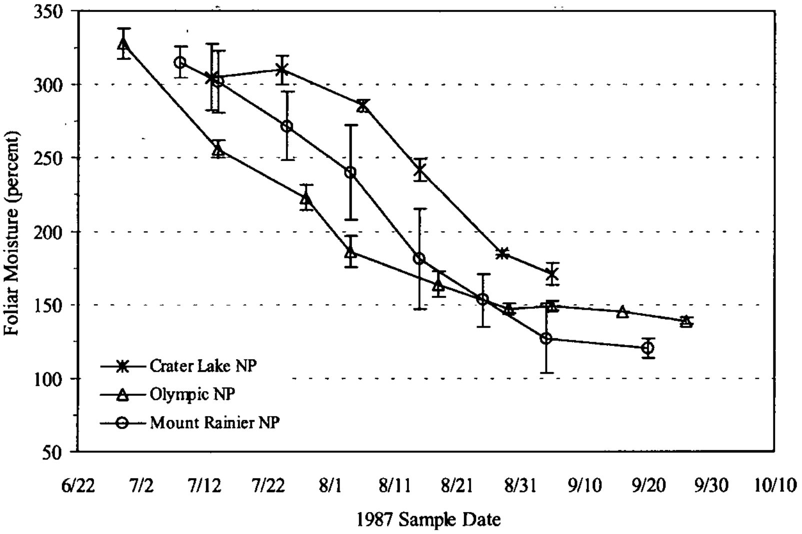

Fig. 2. Percent moisture content of new foliage for *Abies lasiocarpa* at Olympic and Mount Rainier National Parks, and of *Abies magnifica* var. *shastensis* at Crater Lake National Park, 1987.

changes of older foliage (Table 3) were minimal in the 2000 sampling.

3.3. Shrubs, grass, and lichens

In upland dry forests, shrub and grass moisture levels declined gradually through the summers of 1995 and 1996 (Fig. 4). Shrub moisture content exceeded 125% for the entire season in both years. Shrub and grass moisture levels were similar in June (~175%), but the curing of grass fuels resulted in late season moisture content of ~80% compared to a minimum of 125% for shrubs. In 1997 and 1998 (Table 2) curing of grass fuels resulted in a larger

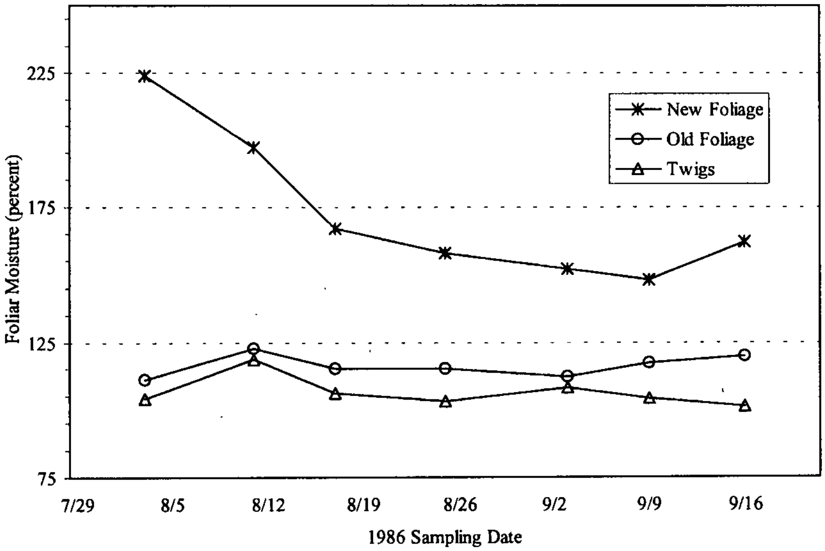

Fig. 3. Percent moisture content of new foliage, older foliage, and small live twigs (<0.5 cm diameter) of *Abies lasiocarpa* at Olympic National Park, 1986.

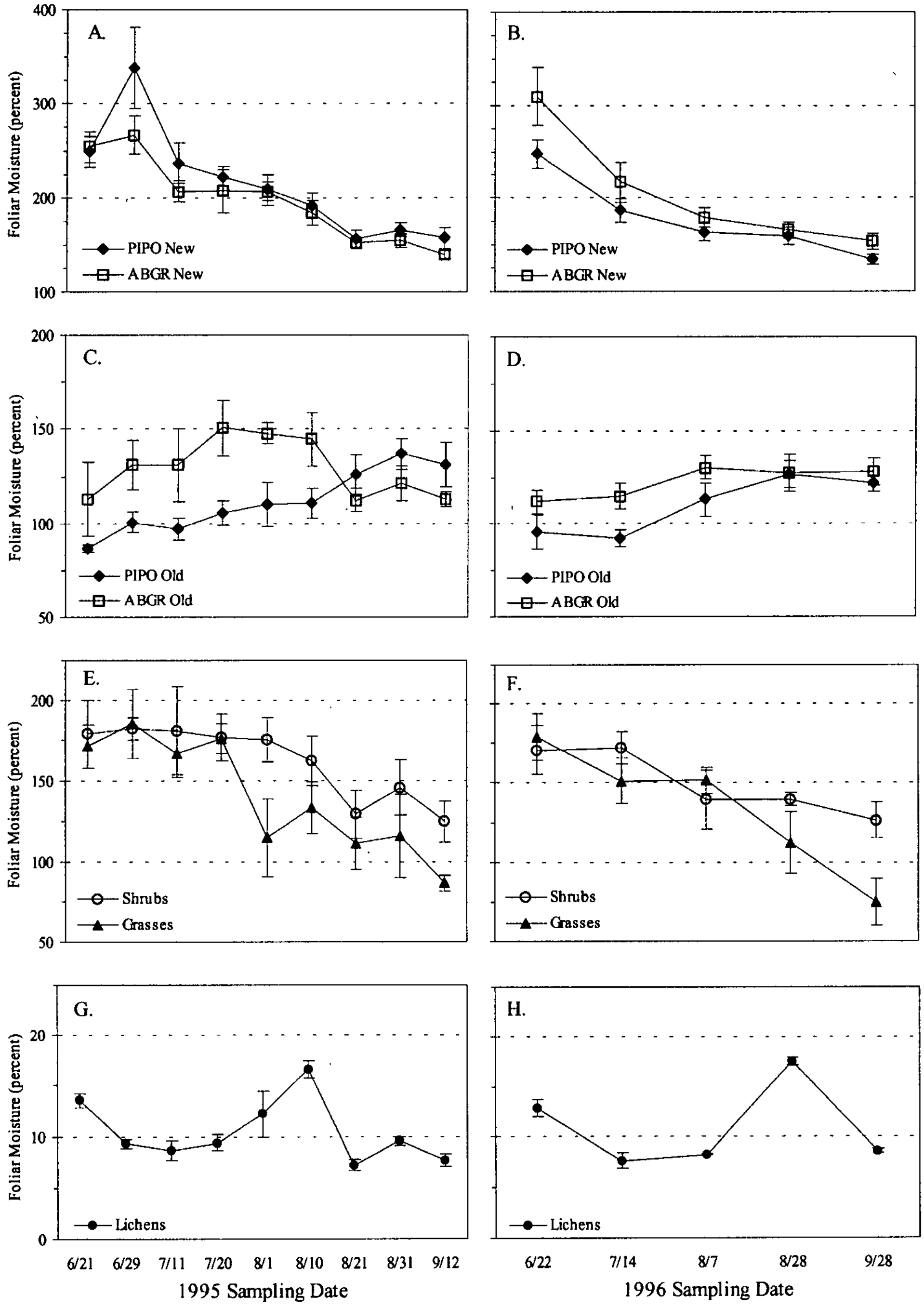

Fig. 4. Percent foliar moisture for new and older ponderosa pine and grand fir needles (A–D), shrubs and grasses (E–F), and lichens (G–H) in 1995 and 1996, Teanaway site.

Table 2
Foliar moisture content (%) of trees, shrubs, herbs, and lichens in early and late season, 1997 and 1998, Teanaway River Valley[a]

Foliar component	1997		1998	
	19 June	6 October	18 June	30 September
Ponderosa pine: new foliage	275 (21)	157 (9)	236 (10)	149 (7)
Ponderosa pine: old foliage	94 (5)	120 (7)	85 (4)	116 (10)
Grand fir: new foliage	313 (10)	190 (47)	292 (15)	167 (4)
Grand fir: old foliage	118 (5)	138 (4)	112 (10)	132 (5)
Shrubs	172 (20)	137 (14)	175 (13)	117 (7)
Grasses	210 (22)	38 (7)	168 (14)	41 (5)
Lichens	14 (0.4)	6 (0.4)	16 (0.4)	8 (0.3)

[a] Sample size: five for all components and standard deviation (S.D.) is shown in parentheses.

Table 3
Diurnal trends in foliar moisture content of 1-year-old foliage of three conifers, Teanaway River Valley, Washington, on 22 August 2000[a]

	Time of day (h)				
	1-year-old foliage				New foliage
	10.00	12.00	14.00	16.00	14.00
Ponderosa pine	138	134	137	138	179
Grand fir	147	137	137	144	184
Douglas-fir	140	128	130	128	173
Relative humidity (%)	35	18	18	20	

[a] Each value is the average of two samples. Maximum temperature of the day was 29 °C at 15.00 h.

disparity between shrub and grass moisture content. Lichen moisture content appeared to react more like a dead fuel (e.g. 1 h timelag dead fuel, <0.63 cm diameter) than a live fuel. Lichen moisture content exceeded 15% on only three sample dates, once each in 1995, 1996, and 1998. There was little variation among sample replicates, most values being between 7 and 10%.

3.4. Riparian and upland foliar moisture

Conifer foliar moisture differed minimally between riparian and upland sites in the *P. menziesii* and *A. grandis* series (Table 4). However, shrub and herb foliar moisture was much higher for the riparian component of these series. Herbaceous foliar moisture was also much more variable in the riparian forests, perhaps reflecting a more diverse assemblage of herbaceous plants. The upland tree and herb samples in the *A. lasiocarpa* series showed slightly higher foliar moisture than the riparian samples, perhaps because small headwater area sampled did not have a well-developed riparian zone. Shrub foliar moistures were similar. Most values were within the range of previously described data for these species or species groups.

Table 4
Late season foliar moisture content (%) in riparian and upland forests in three forest series, Baker City watershed, northeastern Oregon[a]

Forest series	Overstory trees		Shrubs		Herbs	
	Riparian	Upland	Riparian	Upland	Riparian	Upland
Pseudotsuga menziesii	143 (18)	135 (10)	198 (13)	122 (16)	289 (60)	71 (8)
Abies grandis	146 (11)	153 (12)	234 (18)	125 (16)	197 (78)	105 (13)
Abies lasiocarpa	120 (6)	138 (7)	131 (3)	136 (29)	107 (6)	125 (16)

[a] Sample size is four and standard deviation (S.D.) is in parentheses.

Sample sizes required to accurately estimate foliar moisture were calculated using late season samples. Samples sizes calculated for each year from 1995 to 1998 for ponderosa pine and grand fir older needles showed an average of four replicates of 30 g dry weight will be sufficient to estimate foliar moisture within 10% of the mean 95% of the time. Within each species the sample size required by year varied from 2 to 9.

4. Discussion

The moisture content of a tree crown during the summer dry season in the Pacific Northwest will depend on the ratio between current year and older foliage, and whether it is early or late in the season. The ratio of current year to older foliage varies by species, elevation, site fertility, and light (Reich et al., 1995). Elevation, site fertility, and exposure to light are associated with longer leaf life spans. In Washington, lower elevation Douglas-fir has an average leaf life span of 4–5 years (Turner, 1977), while higher elevation Pacific silver fir (*Abies amabilis*) has a leaf life span of 12 years (Brooks, 1987). The influence of bud flushing on weighted crown moisture content should therefore be less for higher elevation conifers, as a higher proportion of the total crown foliage is older foliage with stable, lower moisture content. Observation of torching in trees soon after bud flush (Fig. 5) indicates that only the older foliage and twigs burn, leaving a green shell of limp new foliage on the exterior of the tree crown. After bud flush, the high moisture content of new foliage makes crown fire behavior at a stand level unlikely until later in the season when new foliage moisture content converges with that of the older foliage.

From the results of this study, minimum foliar moisture values appropriate to use in Pacific Northwest crown fire risk assessment appear to be in range of 100–120%. Both current year and older foliage are approaching these values late in the season. This is on the high end of the 75–130% range outlined by Alexander (1988). There was little variation in late season foliar moisture at Teanaway between years that were "wet", "dry", and "average" (Table 2, Fig. 4), consistent with Alexander's review of the literature across North America. Diurnal variation in foliar moisture was present but the variation was small and changes critical flame lengths required for torching by only 0.1–0.3 m. Nevertheless, sampling mid-day (12.00–16.00 h) as recommended by Philpot (1965) seems appropriate to minimize this source of variation.

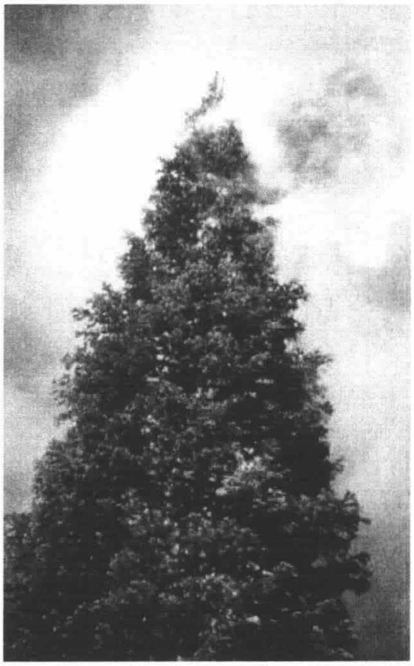

Fig. 5. Fire in the crown of an *Abies concolor* (white fir) tree in June. Only the interior older foliage and twigs are burning. Several minutes later, the exterior of the tree remains green, although the tree died soon thereafter.

Low foliar moisture in early spring has been associated with crown fire behavior in eastern and northern North America (Alexander, 1988; Norum and Miller, 1984), and this has been used as a prescription variable in prescribed burning in subalpine forests (Woodard et al., 1983). In the Pacific Northwest there is little fire activity during this period due to deep snow loads. However, spring crown fires can occur (Huff, 1988), apparently due to crown desiccation following several days of warm weather when tree roots are still in close to freezing conditions. Evapotranspiration is increased, but water conduction in roots is restricted (Hinckley et al., 1984) and foliar moisture may decline. In stands with dense crowns, fire can move through tree crowns and spread across stands that may have 1–2 m of snow on the ground. This has been observed in both Oregon and Washington (Gary Mills, Willamette National Forest, Oregon; Robert Dunnagan, Mount Rainier National Park, personal communication), but is considered an unusual type of event for the Pacific Northwest (Agee, 1993).

Our methods for sampling understory shrubs and herbs combined live plus dead categories, and also combined different species, both deciduous and evergreen. This differs from other approaches where individual species might be monitored over time. We did this specifically to represent the fuels and moisture contents that wildland fires would encounter as they burned through the forest. The variability we encountered by mixing disparate categories of fuel in one sample replicate did not result in substantially increased variability in the results. The average coefficient of variations for all shrub and herb sample dates from 1995 to 1996 (Fig. 4) were 9 and 12% compared to 6–7% for the conifer samples, but still show consistent trends over the season. Where the objective of sampling is to evaluate the moisture content of a fuelbed rather than that of individual species, the mixed sampling is appropriate, and was within the levels of variability seen for individual species.

Mixed-conifer stands treated either by prescribed fire or by mechanical thinning to reduce crown fire hazard will have reduced overstory tree density and canopy cover. Understory vegetation will respond to the increase in available light, nutrients, and/or moisture (Pase, 1958; McConnell and Smith, 1970), increasing potential understory fuels. However, if these fuels maintain high foliar moisture levels, they will dampen surface fire spread and act to shorten the active burning season. Using a Northern Forest Fire Laboratory (NFFL) fuel Model 9 for hardwood litter and long-needled pine litter with no associated understory (Albini, 1976, Table 5), potential surface fire flame lengths will increase with moderate slash disposal techniques that result in higher dead fuel loading (loading intermediate between NFFL Model 9 and NFFL Model 11 (light slash)). After several years of "green-up" but similar elevated dead fuel loads, under identical weather conditions, flame length will decrease by about 20% (Fig. 6). In late season, when curing of grasses occurs and shrub foliar moisture declines, this dampening effect on fire behavior may not be present, but our foliar moisture data suggest that a mitigating effect will last into September for grass-dominated understories and into October for shrub-dominated understories. Perennial grasses and herbs dominate our sites, and these implications would not apply where the dominant understory response to thinning was by annual grasses.

Table 5
Simulated fuel changes after thinning with moderate slash disposal and subsequent green-up through development of a shrub/herb understory[a]

Fuel parameter[b]	NFFL[c] Model 9	Thinned stand	Green-up
1 h load	6.56	8.98	8.98
10 h load	0.92	6.74	6.74
100 h load	0.34	6.74	6.74
Live herb load	0.00	0.00	2.24
Live woody load	0.00	0.00	4.49
Fuel depth (m)	0.06	0.15	0.15

[a] Values for the thinned and green-up conditions are for demonstration and not based on data from any single site.

[b] Load in mg/ha.

[c] NFFL: Northern Forest Fire Laboratory fuel models (Albini, 1976).

The riparian portion of the study showed that understory vegetation in riparian zones tended to be moister later in the season than in drier upland forest types. Although the zone of altered microclimate may be narrow (Williamson, 1999), higher relative humidities within the riparian zones of small streams in dry forests (Danehy and Kirpes, 2000) may be due to higher evapotranspiration from more moist foliage. Higher foliar moisture in understory plants will be associated with lower surface fireline intensities as

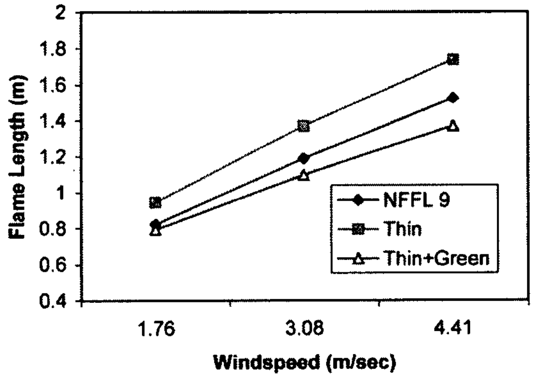

Fig. 6. Effect of altering understory fuels on potential fire behavior. Fuel conditions are listed in Table 5. Environmental conditions are "moderate" with 1, 10, and 100 h timelag fuel moistures at 6, 7, and 8%, and live fuel moisture at 120%. Slope is 30%.

fires approach the riparian zone, even where fire return intervals have been shown to be similar between riparian and upland sites (Olson, 2000).

The importance of lichens to tree crown flammability has long been recognized (Morris, 1934), but quantification of the effect is difficult. Lichens have by far the lowest moisture content of living material in the crown, and lichen moisture parallels the moisture content of the finest dead fuels. During a crown fire in Olympic National Park, foliar moisture content of arboreal lichen (*Alectoria* spp.) was 9% while conifer needles had moisture content ranging from 106–130% (Agee, unpublished data). However, the total lichen mass in any tree is usually quite low, usually less than 5% of tree foliar biomass, even in old-growth western Cascade forest (McCune, 1993; Agee and Huff, 1987). A weighted average moisture content integrating lichen moisture with that of other live fuels masks the importance of fine, dry lichen fuels in carrying flames into the tree crown. The preference of some lichens for true firs, together with the low branching of the firs, makes the firs more susceptible to lichen burning than other tree genera in drier forests.

The sample sizes required for accurate foliar moisture content estimation were much lower than those recommended by Weise et al. (1998) for a variety of western shrubs and conifers. Their required samples sizes for an equivalent error ranged from 1 to 157, with almost half requiring more than 30 samples, in contrast to our range of 2–9. Several reasons may account for this error. There may be higher individual site variability in the Weise et al. (1998) study, which ranged from California chaparral to Arizona and Colorado shrub and forest ecosystems. Individual sample mass varied in their study, with larger sample masses having lower required sample sizes (Weise, USDA Forest Service, personal communication). The techniques used in sampling individual plants affect variability, too. We restricted our conifer sampling to the south sides of the lower crowns of trees, and separated current year foliage from older foliage. We recalculated required sample sizes by simulating a mix of new and older foliage moisture contents in the sample size calculation for each species by year. This would be equivalent to having a crew sample the new foliage for one sample, older foliage for the next sample, up to a sample size of 10. Sample size calculations were much larger: 3–170 samples would be needed to estimate foliar moisture 95% of the time within 10% of the true mean. Almost half required sample sizes greater than 30, as in the Weise et al. (1998) study. Separating new from older foliage will reduce variability, and associated required sample sizes, for ponderosa pine and grand fir, and likely for other tree and shrub species.

5. Conclusions

The progression of crown foliar moisture over the dry season, represented by a weighted average of new and older foliage in the crown, suggests that crown fire potential should be higher late in the dry season. For most crown fire initiation modeling in Pacific Northwest forests, foliar moisture values of 100% should adequately represent late season crown foliar moisture.

Green understory, because of its high foliar moisture compared to cured understory or absence of understory, will have a dampening effect on surface fire behavior. This effect can be significant in thinned forests after several years of green-up. In low elevation, interior forests such as those with ponderosa pine, Douglas-fir, and grand fir, higher understory foliar moisture in riparian areas should dampen surface fire behavior compared to upland forests late in the dry season.

Sample sizes needed to estimate conifer foliar moisture of grand fir and ponderosa pine within 10% of the mean 95% of the time are much lower than those estimated for other western United States vegetation types (Weise et al., 1998). Local evaluation of required sample sizes for specified levels of accuracy is recommended before long-term foliar moisture sampling is initiated in other areas.

The influence of the low moisture content of lichens on crown fire initiation and spread cannot be evaluated by weighting lichen moisture content with that of the tree foliage. Further work is suggested to better quantify the effect of lichens on crown fire behavior.

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