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Seasonal variation in surface fuel moisture between unthinned and thinned mixed conifer forest, northern California, USA

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Abstract. Reducing stand density is often used as a tool for mitigating the risk of high-intensity crown fires. However, concern has been expressed that opening stands might lead to greater drying of surface fuels, contributing to increased fire risk. The objective of this study was to determine whether woody fuel moisture differed between unthinned and thinned mixed-conifer stands. Sections of logs representing the 1000- and 10 000-h fuel sizes were placed at 72 stations within treatment units in the fall (autumn) of 2007. Following snow-melt in 2008, 10-h fuel sticks were added and all fuels were weighed every 1–2 weeks from May until October. Moisture of the 1000- and 10 000-h fuels peaked at the end of May, and then decreased steadily through the season. Moisture of the 10- and 1000-h fuels did not differ between unthinned and thinned stands at any measurement time. The 10 000-h fuel moisture was significantly less in thinned than unthinned stands only in early to mid-May. Overall, even when fuel moisture varied between treatments, differences were small. The long nearly precipitation-free summers in northern California appear to have a much larger effect on fuel moisture than the amount of canopy cover. Fuel moisture differences resulting from stand thinning would therefore not be expected to substantially influence fire behaviour and effects during times of highest fire danger in this environment.

Additional keywords: fire behaviour, fuel reduction treatments, large-diameter fuels, microclimate.

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Introduction

Fire suppression and past logging have both contributed to greater stand density and unnaturally high fuel loading in many parts of the western USA (Taylor 2000; Skinner and Taylor 2006), increasing the risk of stand-replacing fires (Pollet and Omi 2002; Agee and Skinner 2005; Stephens *et al.* 2009). Fuel reduction treatments such as mechanical thinning or prescribed fire are being used to modify stand structure with the goal of reducing the probability of high-intensity wildfire. The objective is generally to reduce surface and ladder fuels, decrease crown bulk density and canopy tree connectivity, and increase height to the live crown in an attempt to separate the linkage between surface and canopy fuels (Van Wagner 1977; Youngblood *et al.* 2008). Many of these treatments have been shown to be effective at reducing the likelihood of stand loss resulting from wildfires (Pollet and Omi 2002; Agee and Skinner 2005; Raymond and Peterson 2005; Ritchie *et al.* 2007). Despite such evidence, there is still uncertainty about the direct and indirect effects of thinning treatments on microclimate and fuel moisture (Agee and Skinner 2005).

Opening the canopy directly alters the microclimate in a forest, potentially leading to lower relative humidity and higher temperatures from increased solar radiation as well as greater surface and subcanopy winds (Harrington 1982; Agee *et al.* 2000; Meyer *et al.* 2001; Whitehead *et al.* 2006). These changes can increase evaporation, which may enhance fuel drying (Countryman 1956; Harrington 1982). Conversely, open stands with lower leaf area intercept less precipitation, meaning that more water potentially reaches the forest floor, which can lead to higher fuel moisture in dead fuels following precipitation events (Samran *et al.* 1995; Whitehead *et al.* 2006). As a result, the ignition potential may be lower in open-canopy forests during lightning events that are accompanied by rain.

The majority of studies to date have investigated the effect of thinning on live fuels (Faiella and Bailey 2007), litter (Whitehead *et al.* 2006) and smaller (≤76-mm diameter) dead woody fuels (Murphy *et al.* 1965; Whitehead *et al.* 2006; Faiella and Bailey 2007). In most of these studies, smaller dead woody fuels have been elevated over the forest floor, approximating worst-case-scenario moisture conditions. These conditions may not be representative of actual fuel moisture on the forest floor at certain times of the year. No studies that we are aware of have compared seasonal trends in moisture levels of larger-diameter (>76 mm) woody fuels between unthinned and thinned stands. Although larger-diameter fuels are not considered important to spread in fire models, they do strongly influence fire effects (Agee *et al.* 2000) and contribute to extreme fire behaviour through production of large amounts of heat energy, which increases crowning and spotting potential (Harrington 1982; Brown 2003). Consumption of these larger fuels increases as decomposition progresses (Knapp *et al.* 2005; Stephens *et al.* 2007; Uzoh and Skinner 2009). Decomposed large woody fuels are also receptive to ignition by embers, especially when dry.

The objective of this study was to evaluate the effect of forest thinning on fuel moisture conditions during the late spring to early fall (autumn) dry period in a western USA coniferous forest. To determine the interaction of unthinned and thinned treatments and sampling time, moisture-loss curves were developed through the fire season for three fuel size classes (10-, 1000- and 10 000-h diameter). Knowing the rate and extent of moisture loss of both small- and large-diameter woody fuels will allow a better understanding of how thinning treatments potentially influence fire behaviour and effects.

Methods

Study site

The previously established replicated forest structure treatments are part of the South Cascades Fire and Fire Surrogate Study (41°58′N, 121°28′W), situated within the Goosenest Adaptive Management Area on the Klamath National Forest, ~4.5 km east of Tennant, CA (Fig. 1). Elevation in the study area ranges from 1480 to 1780 m. The climate in this region is montane Mediterranean with wet, cool winters and warm, dry summers. Annual precipitation averages 760 mm, with most falling from November through April. The vegetation is mostly interior ponderosa pine–mixed conifer forest with lesser amounts of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), incense-cedar (*Calocedrus decurrens* (Torr.) Florin), sugar pine (*Pinus lambertiana* Douglas), Jeffrey pine (*Pinus jeffreyi* Balf.), white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), Shasta red fir (*Abies* × *shastensis* (Lemmon) Lemmon [*magnifica* × *procera*]), lodgepole pine (*Pinus contorta* Douglas ex Louden) and western juniper (*Juniperus occidentalis* Hook).

Whereas the South Cascades Fire and Fire Surrogate study included additional treatments, we focussed on the stand-structure

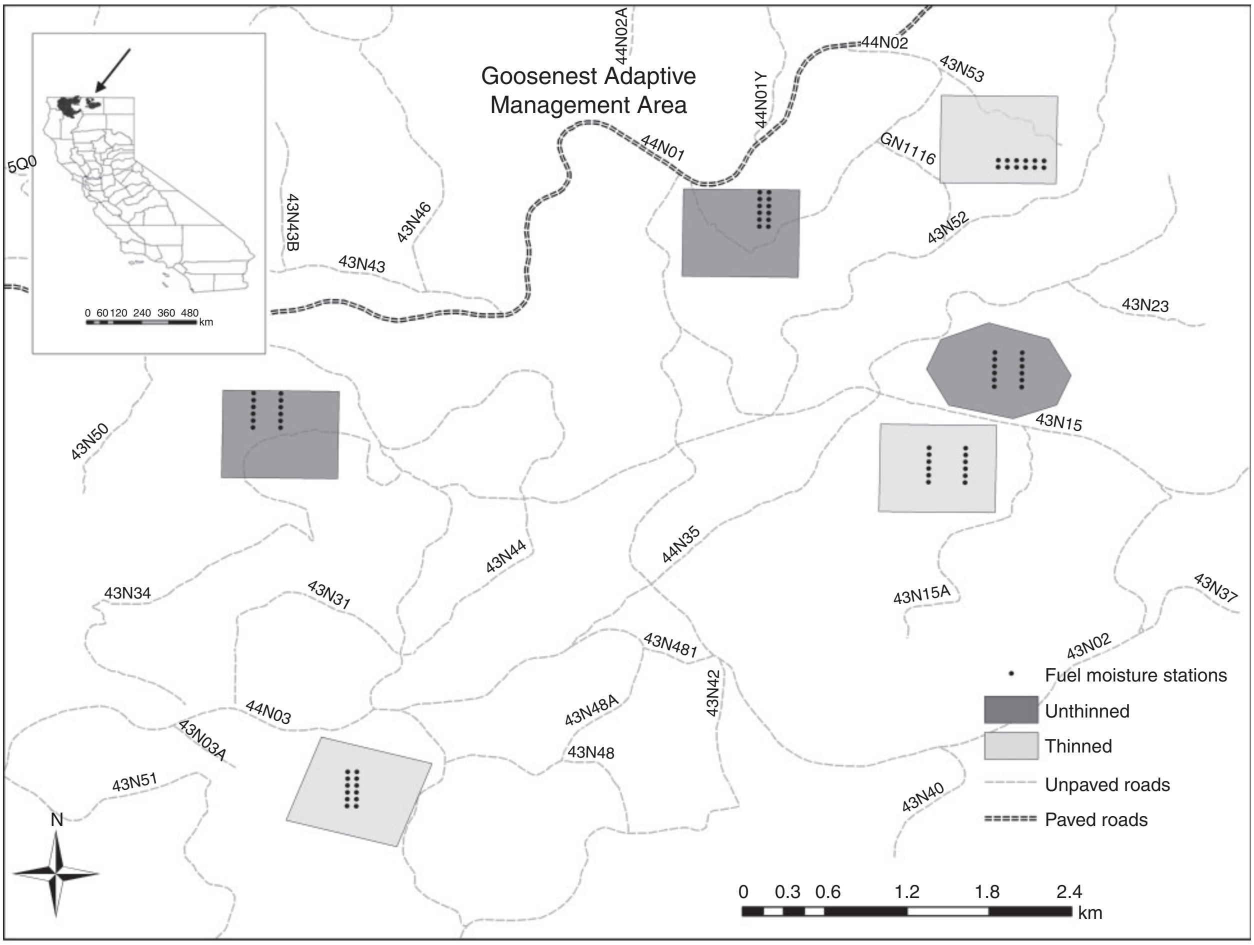

Fig. 1. Map of the thinned (+ prescribed fire) and unthinned units of the South Cascades Fire and Fire Surrogate study within the Goosenest Adaptative Management Area, (41°58′N, 121°28′W), located in the eastern portion of the Klamath National Forest (shaded in black on the California inset map) and 4.5 km east of Tennant, CA. Locations of fuel moisture stations within each treatment unit are identified on the map.

extremes, namely, three untreated control units (unthinned) and three mechanical thinning + prescribed fire (thinned) units (Fig. 1). The unthinned treatment received no form of management except continued fire exclusion (Ritchie 2005). The thinned treatment had an overall goal of increasing the dominance of large pine trees and improving pine establishment of a second-growth forest, through thinning from below, preferentially removing firs that had become established when the site recovered from 1920s logging under a regime of fire exclusion. It was thinned (~1998) in lower-diameter classes, retaining all pines greater than 30 cm DBH (diameter at breast height). This was followed by prescribed fire in the fall of 2001. Each unit was 10 ha in size.

Forest structure

Forest overstorey and midstorey structure differed substantially between the unthinned and the thinned units (Schmidt *et al.* 2008; Stephens *et al.* 2009). Unthinned units post treatment (~2004) averaged 2030 trees ha^{-1} with a basal area of 44.5 m^2 ha^{-1}, whereas the thinned units averaged 121 trees ha^{-1} with a basal area of 18.8 m^2 ha^{-1} (Schmidt *et al.* 2008). Much of the difference in tree density was due to the removal of trees less than 10 cm in diameter. Canopy cover of the unthinned treatment averaged 56%, whereas the thinned treatment averaged 29% (Schmidt *et al.* 2008). Differences between treatments were accentuated by a wind event that toppled more trees in thinned than unthinned units. Thus, the treatments in this study represent the extremes of canopy differences typically witnessed between unthinned and thinned stands.

In 2008, canopy influence was estimated by recording the Leaf Area Index (LAI) at each grid point chosen as a fuel moisture station. Using a LAI-2000 plant canopy analyser (Li-Cor, Lincoln, NE, USA), gap fraction was determined simultaneously at five zenith angles with a fish-eye lens sensor approximately 1 m above the forest floor in four cardinal directions. LAI was then calculated with *LI-COR* software (LI-COR).

Woody surface fuel moisture content

Fuel moisture was defined as the weight of water in the fuel as a percentage of the oven-dry weight of the fuel particles. Fuel moisture sampling took advantage of the existing experimental design within the South Cascades Fire and Fire Surrogate study (Fig. 1). Twelve fuel-moisture stations were established adjacent to 12 randomly selected permanent grid points within each unit (Fig. 1), and one of each of three different woody fuel size classes: 6–25-mm (10-h time lag), 76–229-mm (1000-h time lag), and >229-mm (10 000-h time lag) diameter (Fig. 2) was added to each fuel-moisture station. The time lag refers to the number of hours it takes for moisture of a fuel to reach 63% of the difference between the initial moisture content and the equilibrium atmospheric moisture content (Pyne *et al.* 1996). Both the thinned and unthinned treatments contained natural fuels (besides the samples placed as part of the present study) in the 10-, 1000- and 10 000-h size categories (Schmidt *et al.* 2008; C. N. Skinner, unpubl. data).

For the 10-h fuels, we used a standard fuel stick. The large-diameter fuels (>76 mm in diameter) were mainly butt ends of untreated ponderosa pine telephone poles of nearly equal length and origin. Prior to placing large-diameter fuels in the field, the poles were cut into ~60-cm lengths. The pieces that fell within the 1000-h fuel category ranged in diameter from 155 to 225 mm with an average of 190 mm, and the pieces that fell within the 10 000-h fuel category ranged in diameter from 235 to 360 mm with an average of 300 mm. The largest size class (10 000-h) fuel sections were considerably drier than the 1000-h size class to start, because these logs had dried at the mill for an additional season; the 1000-h sections were from recently cut trees. As this study was focussed on comparing dry-down of fuels between unthinned and thinned stands and not comparing fuel moisture between fuel particle sizes, these initial differences in fuel moistures were inconsequential.

Large-diameter fuels were placed in the field before the first snow (early December 2007), whereas the 10-h fuels were placed in the field following spring snow-melt at the start of sampling. All fuels were placed in contact with the forest floor (Fig. 2). This methodology differs from other previously published studies where fine woody fuels were suspended above the forest floor (Murphy *et al.* 1965; Whitehead *et al.* 2006; Faiella and Bailey 2007). Although this makes comparison with the previous studies of 10-h fuels less direct, fuel moisture values obtained in this way are likely to more closely approximate natural fuelbed conditions (Samran *et al.* 1995). Larger-diameter (1000- and 10 000-h) samples were weighed using a portable scale (50 ± 0.02 kg) and the 10-h fuel sticks were weighed with a standard 10-h fuel-moisture scale. All samples were weighed approximately every 7 days from 9 May 2008 (shortly after snowmelt) through 3 July 2008 and then approximately every 14 days from 23 July 2008 to 27 October 2008, after which the study site became too wet to burn following the onset of fall rains and snows. After the final weighing, the 10-h fuel sticks were collected, dried in a 70°C oven and weighed. To determine the dry weight of the larger (1000-h+) fuel sections, an ~3.25-cm piece was cut from the centre of each section, weighed in the field and transported to the laboratory where it was placed in a 70°C drying oven and reweighed daily until no further weight loss was detected. Final dry weight of each fuel section was then estimated assuming a similar field weight-to-dry weight ratio. This procedure was used instead of drying and weighing the entire 60-cm fuel sections, which was not logistically possible owing to the lack of drying space and the long time that would be required for complete dry-down.

Fig. 2. One set of fuel sticks (10-h) and two size classes of large-diameter fuels (1000- and 10 000-h) were arranged randomly at each of 12 fuel-moisture stations per unit.

Hourly weather data were acquired throughout the duration of the study from the Van Bremmer, CA, Remote Access Weather Station (RAWS) (41°38′35″N, 121°47′38″W), which is located 10 km from the study site. Monthly average daily maximum temperature ranged from 18 to 28°C and monthly average minimum relative humidity ranged from 13 to 33% during the study period, with July and August being the warmest months. A total of 47 mm of precipitation fell in May, 1 mm in June, 10 mm in August, 1 mm in September and 25 mm in October. Temperature, relative humidity, precipitation and 10-h fuel stick moisture allowed us to make comparisons with our field moisture values, and better understand how weather influenced the moisture of all fuel size categories. Field values for both the 10- and 1000-h fuels were also compared with National Fire Danger Rating System (NFDRS) estimates produced for managers by the Wildland Fire Assessment System (WFAS) using the RAWS weather data.

Data analysis

To determine whether a difference in the mean fuel moisture existed between the unthinned and thinned stands and whether these treatment differences changed over time, a repeated-measures mixed model (Littell *et al.* 2006) was used to test for treatment effects on fuel moisture throughout the season. The treatment was considered a fixed effect whereas the subject (10-h fuel stick or large-diameter fuel section within each unit) was considered a random effect. Therefore each specimen within a unit was considered a single subject having independent observations. In all analyses, fuel moisture was transformed to a log scale in order to normalise the variance. The First-Order Ante-Dependence Model (ANTE(1)) was used, which assumes that the variance between observations changes over time. In order to account for a complex covariance structure, a Kenward–Roger (KR) adjustment was applied to the degrees of freedom (Kenward and Roger 1997). The *SAS* (*v.9.2*, SAS Institute Inc., SAS, NC, USA) MIXED procedure was used to estimate the parameters for all analyses. If treatment was significant, post-hoc contrasts were conducted to detect treatment effects. All statistical tests were evaluated at the 0.05α level.

Results

Differences in fuel moisture by fuel size category

Fuel moisture differed significantly between the three fuel size classes (10-, 1000- and 10 000-h) ($P < 0.0001$) (Table 1). Fuel moisture of all fuel sizes varied throughout the sampling period ($P < 0.0001$) (Fig. 3). Moisture of 10-h woody fuels and to a lesser extent the large-diameter fuels (1000- and 10 000-h) was responsive to daily or short-term weather variation (Table 1). Seasonal moisture fluctuations in response to summer drought were far greater in the larger fuel size classes (Fig. 3*b*, *c*). Across stand structure treatments, the 1000-h fuels decreased steadily from a maximum of 115% in May to a minimum of 13% in September (Fig. 3*b*), whereas 10 000-h fuels, which were drier to start, decreased steadily from a high of 69% to a low of 12% in September (Fig. 3*c*). The moisture of 1000-h fuels had decreased to 31% at the onset of the period of highest seasonal fire danger in 2008 (28 July) (Fig. 3*b*), whereas the moisture of the 10 000-h fuels had decreased to 19% by that time (Fig. 3*c*).

Treatment effects on fuel moisture

The canopy LAI was significantly greater in the unthinned treatment (2.6) compared with the thinned treatment (1.1). The forest structure treatment × sampling time × fuel size interaction was highly significant ($P < 0.0001$) (Table 1), indicating that differences in fuel moisture as a result of treatment depended on fuel size and sampling time. Fuel moisture of the 10-h (Fig. 3*a*) and the 1000-h (Fig. 3*b*) fuels did not differ significantly between treatments at any sampling time. There was a trend towards 10-h fuels in the thinned treatment having higher fuel moisture content following rainfall compared with those located in the unthinned treatments (Fig. 3*a*), but this difference was not statistically significant. Only the moisture of 10 000-h fuels differed significantly between unthinned and thinned stands, but only for a portion of the season, with the thinned treatment drier than the unthinned treatment on 9, 15 and 21 May (Fig. 3*c*). No significant differences in fuel moisture between thinned and unthinned stands were observed for any of the fuel sizes during the height of fire season (July through September) (Fig. 3).

Comparison of field and modelled fuel moistures

Field-collected 10- and 1000-h fuel moisture values were consistently higher than measurements taken at a RAWS, or predicted by NFDRS (Fig. 4). The differences between field values and RAWS or NFDRS values were most pronounced when fuel moisture levels were high (field values >20%) (Fig. 4).

Table 1. Mixed models repeated-measures analysis, showing the significance of fixed effects on fuel moisture of different size category fuels throughout the sampling period

Treatment effects	Numerator d.f.	Denominator d.f.	F	$P > F$
Forest structure treatment	1	4.19	0.82	0.4148
Fuel size	2	333	405.17	<0.0001
Forest structure treatment × fuel size	2	333	0.85	0.4303
Sampling time	16	1551	944.53	<0.0001
Forest structure treatment × sampling time	16	1551	10.86	<0.0001
Forest structure treatment × sampling time × fuel size	62	2202	132.06	<0.0001

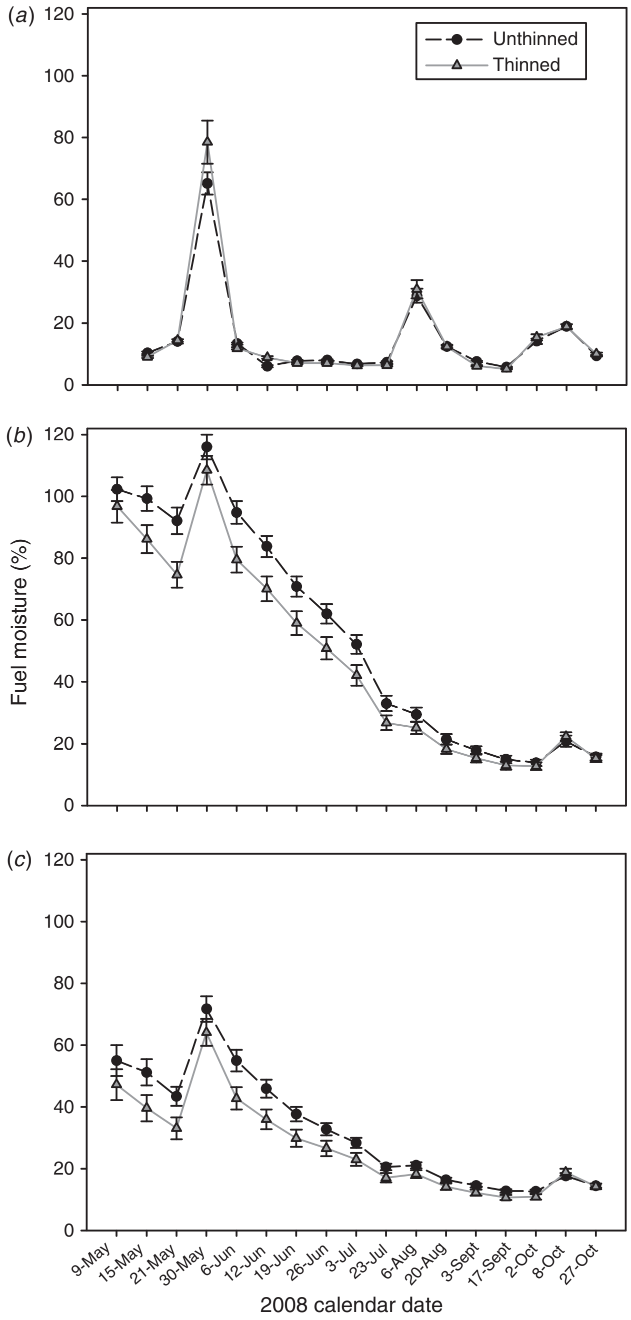

Fig. 3. Mean seasonal variation of (*a*) 10-h, (*b*) 1000-h, and (*c*) 10 000-h fuel moisture and standard error from 9 May 2008 to 27 October 2008 in unthinned and thinned treatments at the South Cascades Fire and Fire Surrogate Site. Note that 1000- and 10 000-h fuel moisture is different at the onset of the study as the 1000-h fuels were from recently cut trees, whereas the 10 000-h fuels had dried an additional season before being placed in the field.

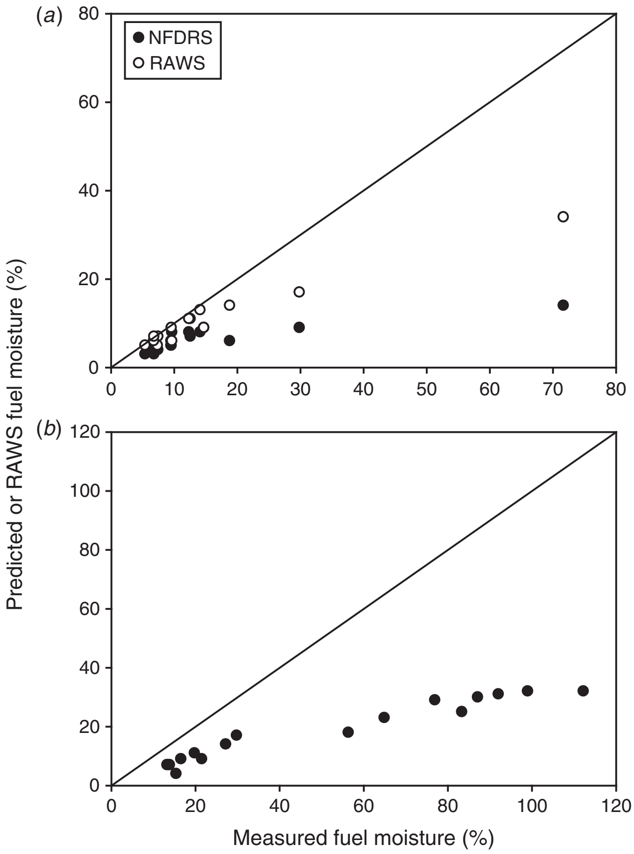

Fig. 4. Moisture (%) of (*a*) 10-h, and (*b*) 1000-h fuels measured in the field at the South Cascades Fire and Fire Surrogate Site versus values obtained from fuel sticks at the nearby Van Bremmer Remote Access Weather Station (RAWS) and values calculated using the National Fire Danger Rating System (NFDRS) by the Wildland Fire Assessment System.

Discussion

Thinning treatments such as those used in this study have been shown to reduce the probability of high-intensity crown fire (Pollet and Omi 2002; Agee and Skinner 2005; Finney *et al.* 2007). In simulations based on the same treatment units used in our study, Schmidt *et al.* (2008) predicted that surface fire spread rates and crown fire potential would be much reduced in the thinned treatment compared with the unthinned treatment under a range of weather conditions. This projected drop in the risk of extreme fire behaviour was the result of lower canopy bulk density due to thinning, and lower surface fuel loading after follow-up prescribed burns. The effect of thinning on fuel-moisture conditions within stands was not investigated in the study of Schmidt *et al.* (2008), but there has been some concern that thinning treatments can alter the microclimate, hastening the dry-down of fuel particles (Countryman 1956; Ingalsbee 2005), potentially increasing the risk of extreme fire behaviour. Results from the present study indicate that surface fuel moisture differences between unthinned and thinned stands were minor, occurring only for larger-diameter woody fuels in the early season, when fuel moisture values are high and fire danger is low. Our study tracked fuel moisture trends over only a single fire season in one location; it is possible that results may not be the same in different precipitation years, or at sites with different understorey conditions, levels of thinning or climate. Still, findings were consistent with previous studies, providing support for potentially wider applicability. Faiella and Bailey (2007) found no significant differences in moisture of 1-h and 10-h fuels between unthinned and thinned ponderosa pine stands in Arizona. Moisture of 100-h fuels in the control treatment was significantly greater than in the thinned treatment on only one sampling date, which followed a rainfall event. Although Whitehead *et al.* (2006) reported significantly lower moisture of 10-h fuel sticks in thinned compared with unthinned stands, they suggested that differences were generally too minor to have much practical effect, and similarly to our study, were noted mainly during times of higher fuel moisture when fire danger is low. Murphy *et al.* (1965) found no significant differences in 10-h fuel moisture in stands thinned to varying degrees. Results of our study suggest that the lack of a strong effect of stand structure on moisture content of dead woody fuels appears to also extend to fuels in contact with the forest floor and not just fuels elevated above the forest floor. Although few studies have compared large-diameter woody fuel moistures under different canopy treatments, our findings corroborate those of Ottmar and Sandberg (1985), who found that the moisture of large woody fuels (1000-h) was nearly identical in partially cut and clear-cut units in western Oregon.

Any effect of thinning on fuel moisture is likely to be greater following precipitation events when fuel moisture levels are high, possibly due to how thinning influences interception of rain and snow by the canopy. The decreased leaf area brought about by thinning means that less precipitation is intercepted by the canopy in thinned stands, allowing more rain and snow to reach the forest floor (Tanskanen *et al.* 2005; Whitehead *et al.* 2006). We noted a trend towards higher moisture of the 10-h fuels in the thinned treatment following late spring and summer rainfall events; however, the differences were never significant. Moisture levels of larger woody fuels are less responsive to individual precipitation events, instead more closely tracking seasonal weather patterns and total available rainfall or snowmelt. In a study in a coniferous forest located near Crater Lake National Park, snow interception in a closed-canopy forest reduced the amount of water stored in the snowpack by more than 50% when compared with an open shelterwood stand (Storck *et al.* 2002). Snowmelt also occurred over a month later in the shelterwood stand (Storck *et al.* 2002). A deeper snowpack coupled with a longer duration of snowmelt could potentially influence the moisture levels of surface fuels, especially larger-diameter woody fuels that require long periods to fully dry. We did not quantify snowpack characteristics or timing of snowmelt in our study units. However, moisture of larger-diameter fuels was not greater in the thinned stands at the beginning of the monitoring period, as would have been expected if the snowpack had lasted longer. It is possible that snowpack differences between closed and more open canopy forests would be greater in locations that receive more winter precipitation and have a deeper snowpack than at this dry site. Although the larger fuels overwintered at the fuel-monitoring stations, the 10-h fuels were deployed too late the following spring to capture any differences in timing of snowmelt.

Thinning can also influence fuel moisture by altering the rate of drying following precipitation events. The removal of forest canopy (e.g. leaf area) directly affects microclimate through increased solar radiation and by allowing more wind to reach the surface fuels, but has surprisingly little effect on ambient temperature or relative humidity (Meyer *et al.* 2001; Whitehead *et al.* 2006). The effect of direct solar radiation on fuel temperatures and fuel moisture can be substantial (Countryman 1977; Rothermel *et al.* 1986). Moisture of surface fuels in contact with the forest floor is also influenced by the moisture content of the duff and soil (Pook and Gill 1993). Capillary water flow from moist duff and soil can slow the drying of upper layers (Samran *et al.* 1995). Drying of all layers is influenced by sunlight, surface temperature and wind, which are expected to be greater in thinned stands. The fact that fuels were consistently somewhat drier in the thinned treatment suggests that the more open canopy of the stand had some small (but not statistically significant) effect on fuel moisture.

Thinning (and fire) can indirectly influence surface-fuel moisture through its effect on understorey vegetation. Understorey vegetation, such as shrubs, responds readily to increases in the amount of sunlight (Murphy *et al.* 1965) and many shrub species become established after fire, through heat- or smoke-stimulated seed germination (Keeley *et al.* 2005). Shrubs can help offset the effects of canopy reduction on surface fuels by providing shade and possibly also through localised increases in relative humidity brought about by transpiration (Murphy *et al.* 1965). In the present study, shrub cover was very low (<2%) in both the thinned and unthinned treatments in 2004, and field observation at the time of this 2008 study indicated that shrubs continued to occupy only a minor portion of the treatment units (C. N. Skinner, unpubl. data). It is possible that understorey shrubs may play a greater role in surface-fuel dynamics in more mesic forested ecosystems where they are often the dominant form of vegetation in the absence of cover by a conifer overstorey.

The longer the time since sustained precipitation inputs and the drier the larger fuels became, the more similar the moisture values between the unthinned and thinned treatments were. At the three measurement days in May when 10 000-h fuel moisture differed significantly between treatments, numerical moisture percentages were on average 11% higher in the unthinned than in the thinned treatments. This difference is unlikely to be important in a fire, because fuel sections in both stand-structure treatments were on average too moist for substantial consumption. During the time of peak fire danger at the end of September and early October, numerical fuel moisture values of these same fuels were within 2% of each other, a difference that was not statistically significant. Ideal drying conditions, with few rainfall events, high temperatures and low relative humidity occurred during the summer of 2008, as is typical of Mediterranean climates. A similar convergence of values to a common low-moisture condition after a prolonged period of drying, regardless of stand structure, was reported in studies by Faiella and Bailey (2007) and Whitehead *et al.* (2006). This suggests that during the driest times of the year when fire danger is the highest, macroclimatic factors such as time since the last precipitation event and seasonal weather variation play a much more important role in regulating surface fuel moisture than factors influencing the microclimate within stands, such as thinning.

Accurate predictions of fire behaviour and effects depend on good estimates of fuel moisture. In the absence of actual field-collected fuel moisture values, fire managers often rely on weather data from RAWS, from which fuel moisture values can be estimated using the NFDRS. Our results show field fuel moisture to be consistently higher than values obtained from a local RAWS (10-h) or values estimated by the NFDRS (all fuel sizes). The magnitude of underestimation was much greater at higher fuel-moisture values. RAWS 10-h fuel stick data and NFDRS estimates are both for fuels elevated off the forest floor, whereas our field numbers were from fuels in contact with the forest floor, which explains some of the discrepancy. The difference between field and estimated values also demonstrates the role of soil and duff moisture in regulating fuel moisture. When the soil and duff moisture are high, as would be expected during the spring or early summer, fuels in contact with the forest floor absorb this moisture through capillary water flow. During dry spells when moisture lost through evaporation exceeds precipitation input, the duff and soil dry down, leading towards a convergence of moisture values between fuels in contact with the forest floor and fuels elevated above the forest floor. Both the RAWS estimates and NFDRS estimates tend to be most reliable for fuel moistures below 20% (Fig. 4). This is similar to findings of Carlson *et al.* (2007), who reported the greatest divergence with NFDRS predictions when field moisture values were greater than 30%.

Implications for management

Data from this study suggest that surface woody fuel moisture is likely to be similar in unthinned and thinned stands during the wildfire season, when fuel moisture values are at seasonal lows. These findings should not be taken to mean that the hazard of high-severity wildfire would not, under certain conditions, be elevated in thinned stands compared with unthinned stands, just that such an effect is unlikely to be caused by differences in the moisture of woody surface fuels. Fire severity can also be influenced by other factors that are potentially affected by thinning, such as the amount of surface fuel present. Although some thinning practices generate substantial activity fuels (Agee and Skinner 2005; Stephens *et al.* 2009), this was limited in the present study because whole-tree harvest was used and a follow-up prescribed burn consumed a large proportion of the remaining surface fuels (Schmidt *et al.* 2008). Thinning can increase surface wind speeds (Weatherspoon 1996) and the added sunlight may cause local increases to surface fuel temperatures, both of which can also potentially influence fire behaviour. However, in terms of fire hazard, it is generally believed that any enhancing effect on within-stand wind speeds and surface fuel temperatures due to thinning small and suppressed trees will be more than compensated for by the reduction in crown fuels, as long as surface fuels are adequately treated (Weatherspoon 1996; Agee and Skinner 2005).

Differences in fuel moisture between unthinned and thinned stands were most prevalent at the end of snowmelt, likely due to how changes in canopy architecture alter interception of precipitation and rate of drying following precipitation. Such differences would be of little consequence to fire managers planning for periods of high wildfire danger, but potentially important in planning for prescribed fire treatments, which are most commonly implemented at the margins of the dry season when fuel moisture levels are higher. Our finding of greater moisture in the largest (10 000-h) fuels in shaded untreated control stands during parts of May suggests that early-season moisture differences could be a consideration for prescribed fire planning if consumption of these larger fuels is a goal.

Knowledge of fuel moisture is critical for predicting behaviour in wildfires, and where forest restoration includes the use of prescribed fire, accurate fuel moisture values allow fire managers to time burning to meet fire effects objectives. Our results demonstrate that the RAWS and NFDRS estimated fuel moisture values are reasonable estimates of worst-case-scenario field values during times of the year when fuel moisture is low, but substantially underestimate field fuel moisture values at other times. This would be particularly applicable to prescribed burns conducted outside the driest times of the year, leading to inaccurate assessments of fire behaviour, fuel consumption and fire effects. Until models are better calibrated for times of the year when surface-fuel moisture levels are higher, timing prescribed fire ignition for optimum results may benefit from field-collected fuel moisture samples.

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