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Canada

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Natural Resources Canada, Canadian Forest Service, Victoria, British Columbia

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Abstract

Thinning of coniferous forest stands is commonly advocated as a means of reducing the probability of crown fires. However, it may also increase surface fuel load, reduce fine fuel moisture content, and increase within-stand wind, which in turn can exacerbate surface fire behaviour and increase crowning potential. Comparison of microclimatic measurements made in a mature lodgepole pine stand (*Pinus contorta* Dougl. var. *latifolia* Engelm.) in southeastern British Columbia to those from an adjacent stand with half the basal area removed by thinning to a 4-m intertree spacing showed a decrease in canopy interception of rainfall and increases in solar radiation, wind speed, and near-surface air temperature as a result of thinning, but very little difference in relative humidity during the daily peak fire danger period. Moisture content of lodgepole pine needle litter and ponderosa pine fuel moisture sticks was lower in the thinned stand in 2005 and 2006, particularly immediately after rain; differences decreased quickly as the fuels dried, resulting in a very small difference under moderate and high fire danger conditions. Predictions of the moisture content of lodgepole pine needle litter based on the Canadian Forest Fire Weather Index System were significantly lower than that measured in the unthinned stand, but again the differences decreased as fuels dried out. The system worked well in both the thinned and unthinned stands at moderate and high levels of fire danger.

Résumé

On encourage couramment l'éclaircie des peuplements résineux comme mesure pour réduire la probabilité des feux de cime. Toutefois, l'éclaircie peut aussi augmenter l'accumulation de combustible de surface, réduire le taux d'humidité des combustibles légers et augmenter le vent à l'intérieur des peuplements, ce qui peut par conséquent exacerber le comportement des feux de surface et augmenter le risque des feux de cime. La comparaison des mesures microclimatiques prises dans un peuplement de pins tordus adultes (*Pinus contorta* Dougl. var. *latifolia* Engelm.) au sud-est de la Colombie-Britannique à celles prises dans un peuplement voisin dont la moitié de la surface terrière avait été éclaircie afin d'obtenir un espacement entre les arbres de 4 m a révélé une diminution de la pluie interceptée par le couvert et une augmentation du rayonnement solaire, de la vitesse du vent et de la température de l'air près de la surface à cause de l'éclaircie, alors qu'une différence minime de l'humidité relative durant la période diurne de risque d'incendie élevé a été notée. Le taux d'humidité dans la litière d'aiguilles de pin tordu et les baguettes hygroscopiques des pins ponderosa était moins élevé dans le peuplement éclairci en 2005 et 2006, surtout immédiatement après une averse; les différences s'estompaient rapidement au fur et à mesure que les combustibles séchaient, ce qui donnait une différence minime dans des conditions où le risque d'incendie est modéré ou élevé. Les prévisions du taux d'humidité de la litière d'aiguilles de pins tordus fondées sur la Méthode canadienne de l'indice forêt-météo étaient beaucoup moins élevées que les mesures prises dans les peuplements non éclaircis; toutefois, les différences s'amenuisaient encore une fois au fur et à mesure que les combustibles séchaient. La méthode a bien fonctionné tant pour les peuplements éclaircis que non éclaircis lorsque le risque d'incendie était modéré ou élevé.

Introduction

Thinning in coniferous forest stands to a wide inter-tree spacing is commonly recommended as means of preventing crown fires from occurring (Graham et al. 1999; Partners in Protection 2003). However, thinning may also increase surface fuel loads, decrease fine fuel moisture levels and increase within-stand winds, thereby elevating potential severity of surface fires and in turn the likelihood of crowning (Agee and Skinner 2005; Keyes and Varner 2006). Rates of wetting or drying, and consequently the moisture content of fine surface fuels, are influenced by microclimatic factors that are expected to change when a stand is thinned. These factors include canopy interception of rainfall, insolation, near surface air temperature and relative humidity, and within-stand wind speed.

The purpose of this study was to compare and contrast microclimatic and fine fuel moisture conditions in a natural stand of mature lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) with an adjacent stand which was thinned to a uniform 4-m spacing between stems with respect to:

- within-stand microclimate elements that are likely to affect the moisture content of fine, dead surface fuels;
- measured moisture content of fine, dead surface fuels; and,
- differences between the actual moisture content of lodgepole pine needle litter versus equivalent values predicted by the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987).

Study Area

The study area is located south of Cranbrook in southeastern British Columbia (longitude 115° 36' W; latitude 49° 25' N), on level terrain in a broad valley at 1350 m elevation. The overstory canopy in the study area consists of a single-cohort lodgepole pine stand that originated after a wildfire in 1912, with a few scattered western larch (*Larix occidentalis* Nutt.) trees of about the same age.

In 1992, one of three adjacent 15-ha to 20-ha treatment units (Figure 1) was commercially thinned by Galloway Lumber Co. Ltd. to a uniform inter-tree spacing of approximately 4 m between stems, a second area was clearcut, and a third was left untreated (Mitchell 1994). Stand characteristics are shown in Table 1 and the associated fuel complex characteristics are presented in Table 2. Sparse understory vegetation is typical of the lodgepole pine/Oregon grape-pinegrass site series of the dry cool Montane Spruce biogeoclimatic subzone (Braumandl and Curran 1992).

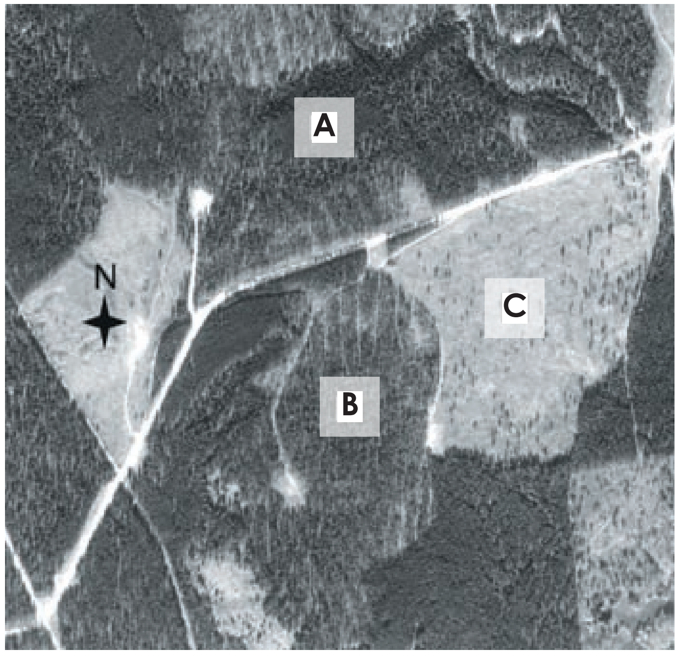

Figure 1. Vertical aerial overview of study area with weather station locations represented by the letters A (unthinned control), B (thinned to 4-m spacing), and C (clearcut).

Table 1. Stand tables for the unthinned control and thinned stands at the Cranbrook study site showing all trees >7.5 cm dbh, by 5-cm diameter classes. (Data from 2003 re-measurement of three permanent sample plots in each treatment unit. Plots were 400 m^2 each in the Control treatment and 625 m^2 each in the Thinned treatment.)

		Mid-point of diameter class (cm)						
		10	15	20	25	30	35	40
Stand	Species	------------------------------ trees/ha --------------------------------						
Control	Western larch	8	0	0	0	0	0	0
	Lodgepole pine	208	700	633	125	17	0	0
Thinned	Western larch	11	5	5	5	5	5	11
	Lodgepole pine	0	11	155	192	53	5	0

Table 2. Description of the fuel complexes in the unthinned control and thinned stands at the Cranbrook study site. (Data collected in July 2005 using methods described in Whitehead et al. (2007)).

Fuel Complex	**Control**	**Thinned**
-------------------- Overstory Conifers (≥7.5 cm dbh) ---------------------		
Basal area (m^2/ha)	40.0	21.7
Density (live trees/ha)	1692	464
Mean height (m)	20.6	21.8
Mean diameter at breast height (cm)	19.4	23.9
Mean live crown base height (m)	14.0	12.8
Mean dead crown base height (m)	5.0	2.4
Maximum live crown width (m)	2.6	3.6
Canopy bulk density[a] - foliage (kg/m^3)	0.204	0.053
------------------------------- Understory Fuels --------------------------------		
Understory conifer biomass (kg/m^2)	0.00	0.03
Shrub biomass (kg/m^2)	0.01	0.16
Herbaceous biomass (kg/m^2)	0.03	0.06
Litter biomass (kg/m^2)	0.18	0.18
Litter bulk density (kg/m^3)	19.0	17.1
Litter depth (cm)	0.9	1.1
Duff bulk density (kg/m^3)	113.5	104.9
Duff depth (cm)	2.7	3.2
Dead woody fuels 0.1 to 3 cm in diameter (kg/m^2)	0.15	0.15
Dead woody fuels 3.1 to 7 cm in diameter (kg/m^2)	0.26	0.15
Dead woody fuels 7.1+ cm in diameter (kg/m^2)	0.81	1.95

[a] Based on foliar weight calculated using equations from Standish et al. (1985)

Researchers from the Canadian Forest Service have studied the efficacy of commercial thinning to uniform wide spacing for reaching several stand-level management objectives on several sites in the east Kootenays. Various studies at this site have examined the harvest operations and effects on stand and tree growth, wildlife habitat, and forest health (Mitchell 1994; Allen and White 1997; Safranyik et al. 1999; Safranyik et al. 2004; Whitehead et al. 2004; Whitehead and Russo 2005). This paper discusses selected microclimatic elements that may affect fuel moisture, based on a 13-year (1993-2005) database and fine fuel moisture content measured in the thinned and unthinned stands during the 2005 and 2006 fire seasons.

Methods

Microclimate Measurements

In 1992, weather stations with dataloggers (Campbell Scientific CR-10) were installed in the centre of each the three treatment units at least 125 m from the outside edge of each unit. Air temperature and relative humidity (RH) sensors (Campbell Scientific HMP 45C) and full spectrum solar radiation pyranometers (LiCor LI200SZ) were mounted on a tower at a height of 1.3 m above ground. Wind speed monitors (RM Young Wind Monitors) were installed at a height of 3.0 m. Three air temperature sensors (Campbell Scientific 107B) were also located near the tower at 5.0 cm above the forest floor. Solar radiation and air temperature sensors at 5.0 cm height were sampled every five minutes, while air temperature and RH measured at 1.3 m height and wind speed at 3.0 m height were sampled every minute. Hourly data summaries and associated statistics were recorded from May 1 through September 15 from 1993 to 2005. Daily precipitation was measured by a Sierra Misco tipping bucket rain gauge only in the clearcut treatment unit until 2003, when gauges were also added in the thinned and unthinned stands. Each rain gauge was mounted 1.3 m above ground-level and 3-5 m from the sensor tower. Two RH sensors were added 5.0 cm above ground in the thinned and unthinned stands in 2006. These were sampled every minute and hourly data were recorded from May 15 to October 11, 2006.

Weather station and sensor maintenance was carried out as per Spittlehouse (1989). Initial screening of raw data followed procedures described by Meek and Hatfield (1994) which included between-sensor comparisons where sensors were replicated on site (e.g., temperature) and where sensors were not replicated (i.e., RH, wind speed, precipitation and solar radiation), and comparison to nearby Environment Canada station normals. Manual filtering and graphical screening were used to account for sensor drift, and records with missing data for any treatment were deleted from the database before analysis.

Moisture Content of Fine, Dead Surface Fuels

Fuel Moisture Sticks

Five sets of ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws) fuel moisture sticks, consisting of four dowels weighing 100 g when ovendry (Nelson 2000), were mounted on wire brackets 20 cm above the forest floor and positioned 2 m apart on an east-west transect (Figure 2) near the weather stations in the thinned and control stands. Each array was weighed on site at 16:00 hrs Mountain Standard Time (MST) on 70 days between June 21 and September 25, 2005, and on 52 days between June 28 and September 12, 2006. Each set of fuel moisture sticks was ovendried at the end of the season to determine how much weight was lost due to weathering effects over the season (Haines and Frost 1978). Moisture content was calculated for each sampling day using Equation 1:

$$\text{Moisture content (\%)} = 100 \times \left(\frac{\text{Wet weight - Dry weight}}{\text{Dry weight}}\right) \qquad (1)$$

with dry weights adjusted for weathering, using equation 2:

$$\text{Adjusted dry weight (g)} = 100 - \left(\frac{100 - a}{b}\right) \times c \qquad (2)$$

where *a* is dry weight (g) at end of season, *b* is total number of days exposed, and *c* is number of days exposed before wet weight was measured.

Figure 2. Fuel moisture stick arrays set up in the thinned stand (left) and in the unthinned control stand (right).

Needle Litter

Ten 1.0 × 1.0 m quadrats, spaced at 1-m intervals on a transect perpendicular to the fuel moisture stick transect, were established in each stand for sampling of lodgepole pine needle litter (Figure 3). Cured lodgepole pine needles were collected from the forest floor nearby and distributed in a thin even layer (~1.5 cm thick) amongst the quadrats on May 18, 2005 and again on May 17, 2006 to ensure ample litter for fuel moisture sampling throughout the season. Five 50-g samples of needle litter were collected from alternating odd and even quadrats each sampling day, at 16:00 hrs MST on 70 days between June 21 and September 25, 2005 and on 52 days between June 28 and September 12, 2006. Each sample was placed in a numbered metal tin and weighed on site to the nearest 0.1 g, then ovendried for at least 24 hours at 100°C and reweighed (Norum and Miller 1984). Gravimetric moisture content of needle litter was calculated using Equation 1.

Figure 3. Plots for sampling lodgepole pine needle litter in the thinned stand before adding needles (left) and in the control stand after adding needles (right).

Predicted Moisture Content of Needle Litter

In Canada, the fuel moisture codes and fire behaviour indices that make up the FWI system are calculated from daily fire weather observations. The BCMOFR Southeast Fire Centre installed a standard fire weather station (Forest Technology Systems Ltd.) in the clearcut opening in order to compute the six standard components of the FWI System, including the Fine Fuel Moisture Code (FFMC) as well as the Fire Danger Class (FDC) (B.C. Ministry of Forests 1983). The FFMC is a relative numerical rating of the moisture content of litter and other cured fine fuels (Van Wagner 1987). We compared the moisture content equivalent of the FFMC calculated using Equation 3 (Van Wagner 1987) to the actual sampled moisture content of lodgepole pine needle litter:

$$\text{Moisture content (\%)} = \frac{147.2 \times (101 - \text{FFMC})}{59.5 + \text{FFMC}} \qquad (3)$$

Data Analyses

Microclimate Elements

Mean hourly within-stand wind speed, total solar radiation, and RH at 1.3 m height above ground, air temperature at 1.3 m and at 5.0 cm above ground during the peak fire danger period each day (12:00 to 16:00 hrs MST) in both stands over 13 fire seasons (1993 to 2005) were compared graphically. RH at 5.0 cm above ground was similarly compared, but data were only available for the 2006 fire season. Precipitation data over three fire seasons (2003 to 2005) were consolidated into 54 "rain events" (periods of one or more days when precipitation was recorded at one or more stations and separated from other events by at least one day without rain). For each rain event, canopy interception of rainfall in the thinned and unthinned stands was calculated using Equation 4 and between-treatment differences were tested with a Wilcoxon signed-ranks test (α = 0.05).

$$\text{Interception (\%)} = 100 \times \left(\frac{\text{Rainfall in clearcut (mm)} - \text{Rainfall in stand (mm)}}{\text{Rainfall in clearcut (mm)}} \right) \qquad (4)$$

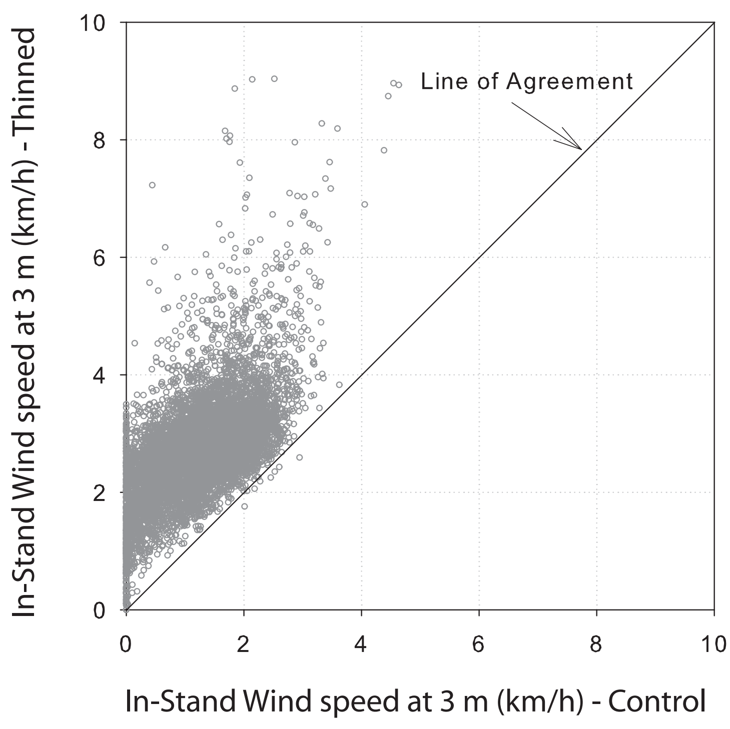

Figure 4. Hourly means of wind speed measured at 3 m height between 12:00 MST and 16:00 MST in the thinned stand vs. corresponding means in the control stand (n = 7380 hours).

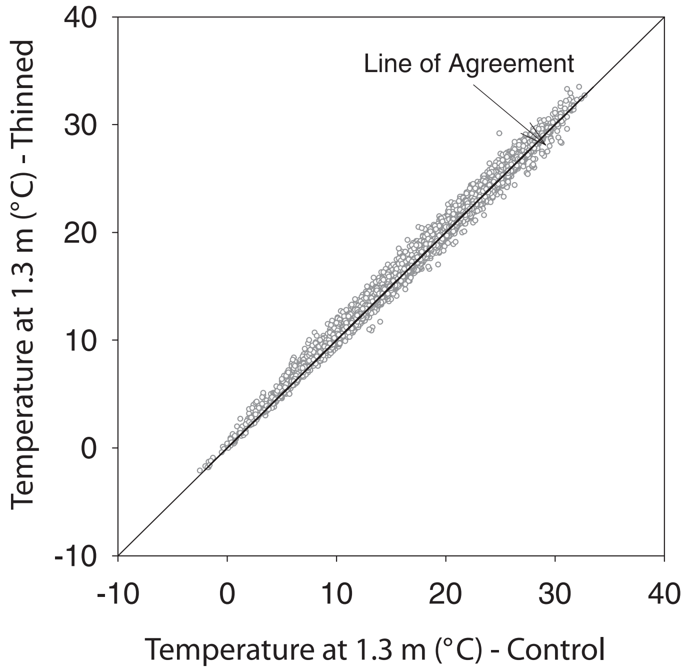

Figure 5a. Hourly means of air temperature measured at 1.3 m height above ground between 12:00 MST and 16:00 MST in the thinned stand vs. corresponding means in the control stand (n = 7760 hours).

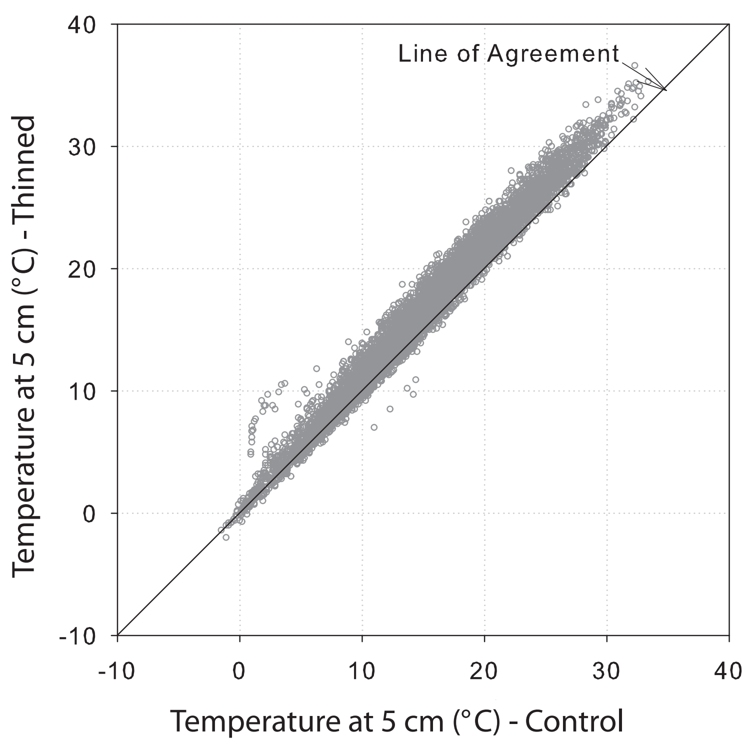

Figure 5b. Hourly means of air temperature measured at 5 cm height above ground between 12:00 MST and 16:00 MST in the thinned stand vs. corresponding means in the control stand (n = 7760 hours).

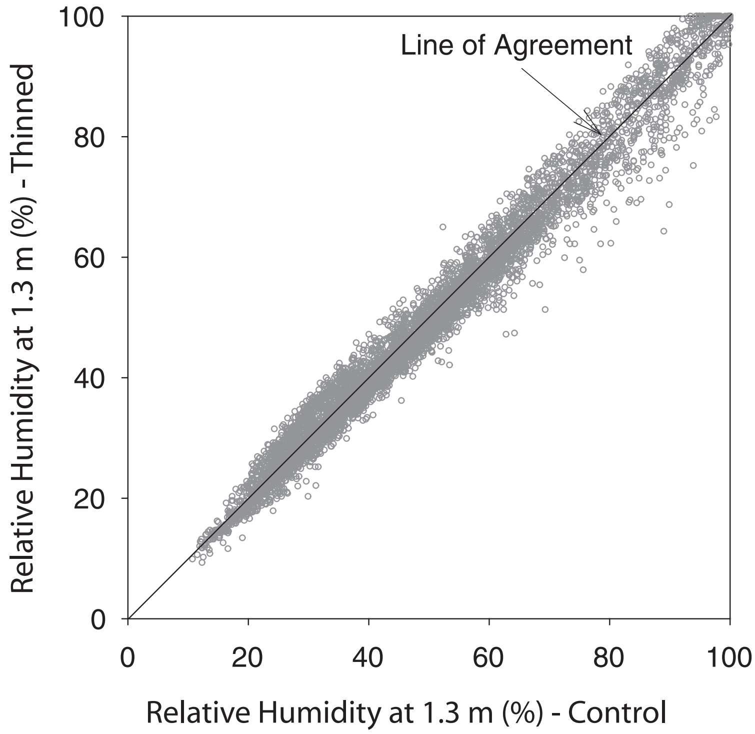

Figure 6a. Hourly means of relative humidity (%) measured at 1.3 m height above ground between 12:00 MST and 16:00 MST in the thinned stand vs. corresponding means in the unthinned control stand (n = 5809 hours).

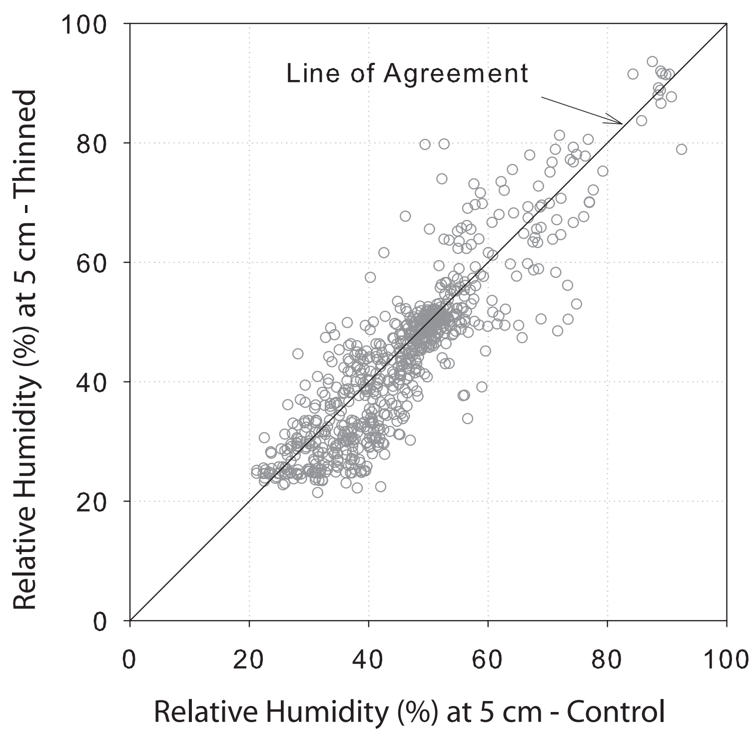

Figure 6b. Hourly means of relative humidity (%) measured at 5 cm height above ground between 12:00 MST and 16:00 MST in the thinned stand vs. corresponding means in the unthinned control stand (n = 731 hours).

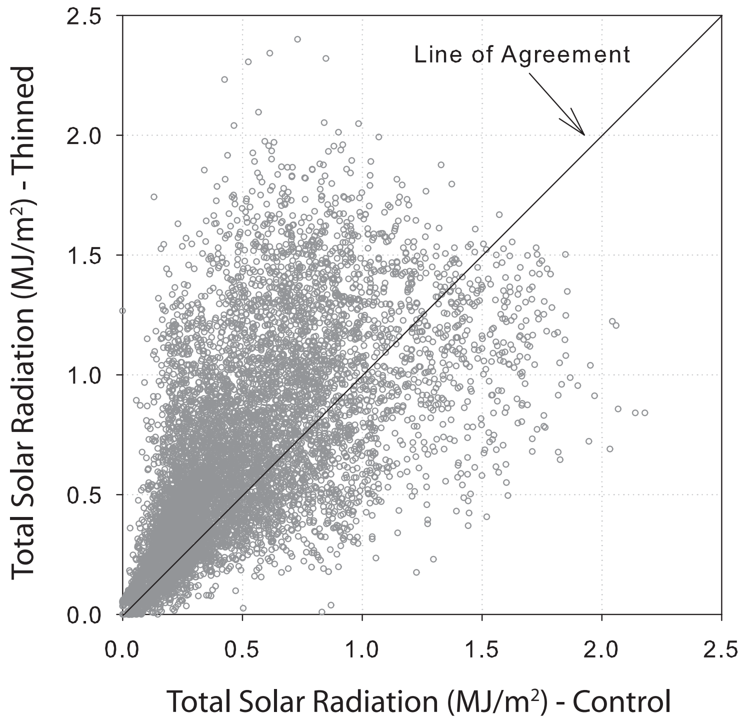

Figure 7. Total hourly solar radiation measured at 1.3 m above ground between 12:00 MST and 16:00 MST in the thinned stand vs. corresponding total hourly solar radiation in the unthinned control stand (n = 8503 hours).

Fine Fuel Moisture Content

The variance was not constant across the range of moisture content data for the fuel moisture sticks and lodgepole pine leaf litter. We grouped the data by FDC for graphical comparisons as it was clear that this problem was associated with recent rainfall events, which occurred primarily when the FDC was Very Low (26 days). During periods when FDC was Low (42 days), Moderate (34 days) or High (20 days), variance in the data was small and consistent. We therefore restricted statistical analyses of between-treatment differences to days with Low, Moderate or High ratings and used two-tailed paired sample t-tests to investigate differences between treatments in moisture content of fuel moisture sticks (α=0.05) and differences in moisture content of lodgepole pine needle litter between treatments, and between each treatment and the predicted moisture equivalent of the FFMC using Equation 3 (α=0.02 to approximate an experiment-wise error of 0.05) (Kirk 1968). All statistical analyses were conducted using Analyse-it® for Microsoft Excel.

Results and discussion

During 54 rain events over three fire seasons, rainfall in the clearcut opening ranged from 0.1 mm in a single day to 99 mm over an 11-day period. Mean canopy interception was significantly lower ($p<0.0001$) in the thinned stand (51.1%; SE = ±2.9254) than in the unthinned stand (65.3%; SE = ±2.9596%) relative to the clearcut opening.

Mean hourly within-stand wind speed, air temperature, RH and solar radiation in the thinned stand during the peak fire danger period each day (12:00 to 16:00 hrs MST) plotted against the corresponding hourly means in the unthinned control stand are shown in Figures 4–7, respectively. Most between-treatment differences were intuitive, with the exception of mean air temperature and RH (within-sensor error ±3%) where there was no between-treatment difference when measured at a height of 1.3 m above the forest floor. However, RH was most often lower and mean air temperatures most often higher in the thinned stand when measured much closer to the surface fuels of interest (at 5.0 cm above ground). Wind speed at 3 m and air temperature at 5.0 cm above ground were consistently higher in the thinned stand. Although total solar radiation was most often higher in the thinned stand, as expected, between-treatment differences were not as consistent as for wind speed and air temperature, which may have been due to effects of shading from one or more trees at a particular sun angle and location relative to the sensors in different treatments.

Daily means of moisture content of fuel moisture sticks in the thinned stand plotted against corresponding daily means in the unthinned control stand are presented in Figure 8 and within FDC categories in Figure 9. Moisture content was generally lower in the thinned stand than in the unthinned stand, but the magnitude of that difference decreases when moisture content is below about 20% and as the FDC increases (Figure 9, Table 3). Variance and between-treatment differences in daily mean moisture contents of needle litter samples were larger than for fuel moisture sticks, but tended to follow the same general trends (Figures 10 and 11, Table 3). Pook and Gill (1993) compared an untreated radiata pine (*Pinus radiata* D. Don) plantation with one that had been thinned and pruned. They also found that, although litter moisture content was generally higher in the unthinned stand, between-treatment differences decreased with time since rain and increasing fire danger conditions.

Table 3. Percent fine fuel moisture content (Mean; ± SE) of needle litter and fuel moisture sticks at different fire danger classes.

Fire danger class		**Litter**	**Moisture sticks**
Low (n=42)	Control	15.9 ±1.04	11.0 ±0.32
	Thinned	12.6 ±0.50	10.2 ±0.27
	Predicted	14.4 ±1.00	
Moderate (n=34)	Control	11.4 ±0.56	9.4 ±0.31
	Thinned	10.0 ±0.54	9.1 ±0.26
	Predicted	11.7 ±0.73	
High (n=20)	Control	10.1 ±0.25	8.8 ±0.16
	Thinned	9.4 ±0.27	8.5 ±0.13
	Predicted	9.2 ±0.28	

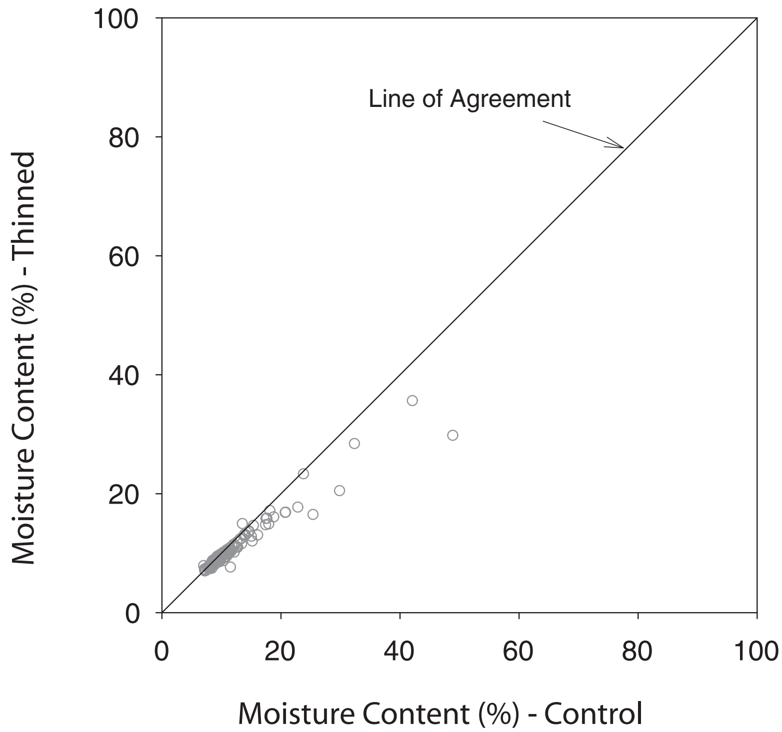

Figure 8. Daily mean moisture content of fuel moisture sticks at 16:00 MST in thinned and unthinned stands on 70 days between June 21 and September 25, 2005 and 52 days between June 28 and September 12, 2006.

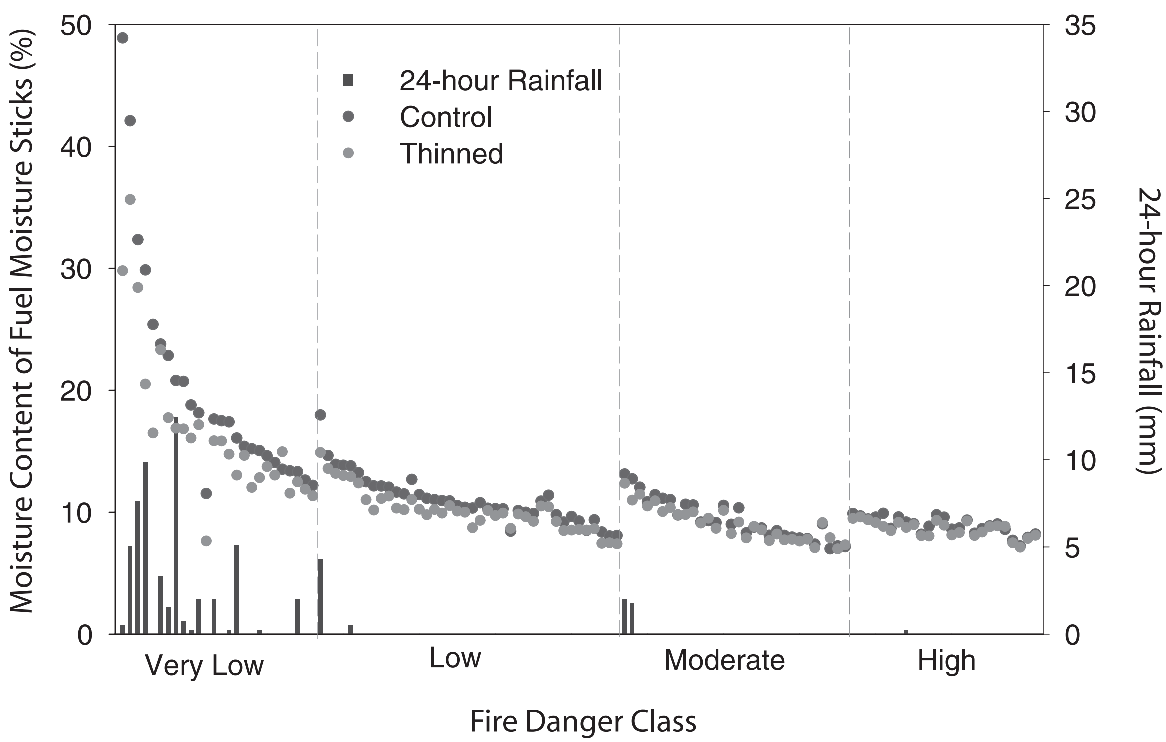

Figure 9. Mean moisture content of fuel moisture sticks in the thinned and unthinned control stands, plotted from wettest to driest control value within different fire danger classes. Corresponding 24-hour rainfall amounts are shown as bars.

Tanskanen et al. (2005) found that canopy characteristics of a mixed Norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* L.) stand in southern Finland, including canopy depth and leaf area index, correlated strongly with ignition success in surface needle litter. They suggested that differences in surface fuel wetting and drying due to canopy influence on precipitation and wind conditions near the forest floor might have been responsible. Canopy characteristics were quite different in the two lodgepole pine stands we studied (Tables 1 and 2) and although we observed a consistent difference in canopy interception of precipitation, wind speed and temperature, the between-treatment differences in moisture content we observed were very small except when fuels were too wet to ignite easily. We found statistically significant between-treatment differences in mean moisture content of both needle litter and fuel moisture sticks when the FDC was Low, Moderate and High (Table 4) but, although statistically significant, it is unlikely that the very small differences we observed in fine surface fuel moisture (0.3% difference in stick moisture content at a Moderate and High FDC, 1.4% and 0.7% difference in litter moisture content at a Moderate and High FDC, respectively) would have any appreciable effect on ignition probability or crowning potential.

Table 4. Two-tailed p values for paired sample t-tests comparing needle litter moisture content (α = 0.02) and fuel moisture stick moisture content (α = 0.05).

	Control vs thinned	**Control vs predicted**	**Thinned vs predicted**	**Control vs thinned**
Danger class	------------------------------------Litter-----------------------------			Moisture sticks
Low	**<0.0001**	**0.0082**	**0.0041**	**<0.0001**
Moderate	**0.0003**	0.7910	**0.0009**	**0.0002**
High	**0.0083**	0.0441	0.6477	**0.0004**

Moisture content of fine surface fuels is one important factor used in the Canadian Forest Fire Behaviour Prediction System to model ignition potential (Lawson et al. 1994), surface fire rate of spread and surface fire intensity (Taylor et al. 1997). When combined with stand characteristics, surface fire intensity is used to predict potential for crown fire. The Fine Fuel Moisture Code generated by the Canadian Fire Weather Index System is an index of moisture content of litter and other cured fine fuels, and is used as an indicator of ignition potential or the potential for fires to start and spread (B.C. Ministry of Forests 1983).

The FFMC moisture content equivalent values predicted using Equation 3 were significantly lower than our measurements of needle litter moisture content in the control or unthinned stand when the FDC was Low and High, and higher than our measurements in the thinned stand when FDC was Low or Moderate (Table 4). When the FDC is High, predicted values are not significantly different than the mean of measured moisture content in either stand (Figure 11, Table 3). Predictions of moisture content of needle litter from daily FFMC values generally improved as fire danger increased (Figure 11). The FFMC is intended to reflect fine fuel moisture content across a fairly wide range of stand conditions within a given fuel type and it appears to be robust enough to predict the moisture content of fine, dead surface fuels such as needle litter in both stand conditions we studied when fire danger is a concern.

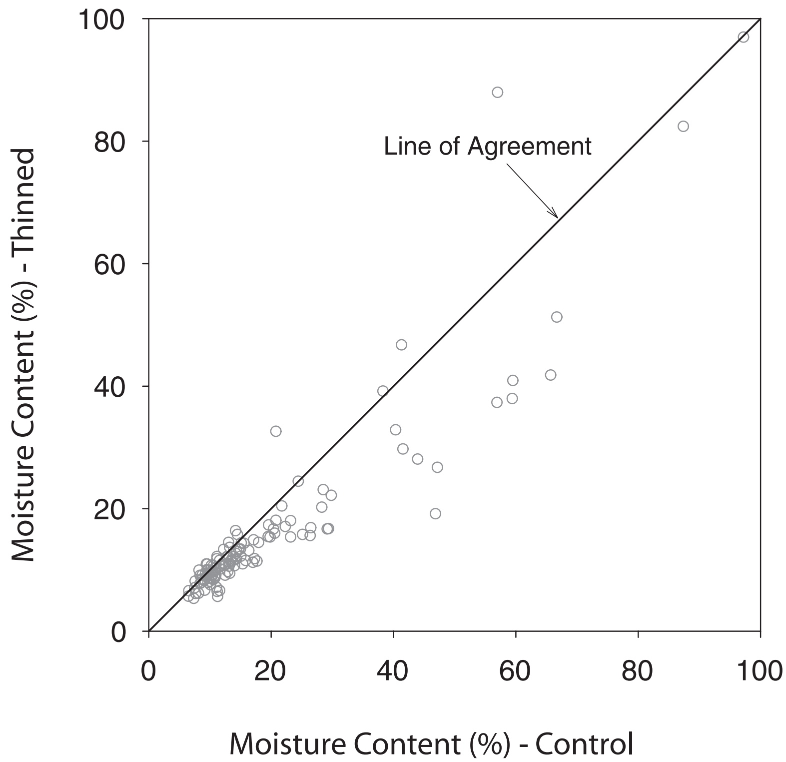

Figure 10. Daily mean moisture content of lodgepole pine needle litter at 16:00 MST in thinned and unthinned stands on 70 days between June 21 and September 25, 2005 and 52 days between June 28 and September 12, 2006.

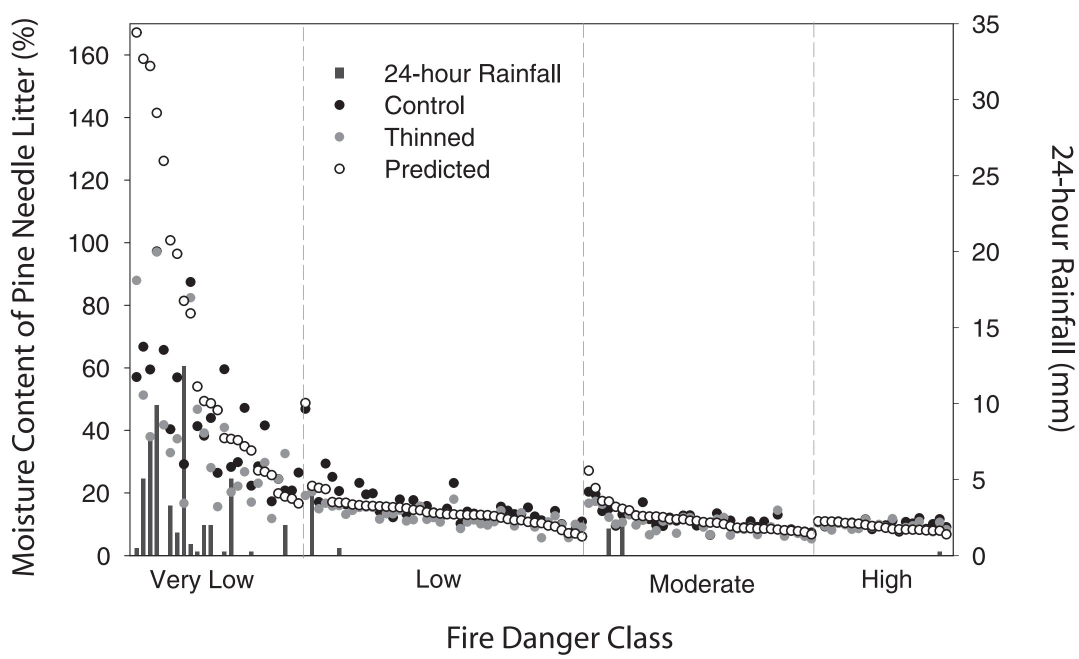

Figure 11. Predicted and mean observed moisture content of lodgepole pine needle litter in the thinned and unthinned control stands, plotted from wettest to driest predicted value within different fire danger classes. Corresponding 24-hour rainfall amounts are shown as bars.

Conclusions

Removing approximately half of the basal area in a mature stand of lodgepole pine in southeastern British Columbia, by thinning from below to a uniform 4-m spacing between tree boles, resulted in decreased canopy interception of rainfall and increased within-stand solar radiation, wind speed, and near-surface air temperature but very little difference in relative humidity or air temperature at 1.3 m height. Moisture content of both needle litter and of fuel moisture sticks showed the greatest differences between the thinned and unthinned stands following rainfall when fire danger was of little concern. These differences decreased rapidly as fuels dried. Under moderate and high fire danger conditions, between-treatment differences were very small and not practically significant. Values for moisture content of lodgepole pine needle litter in both the thinned and unthinned stands were predicted quite well by the moisture content equivalent of the FFMC component of the Canadian Fire Weather Index System. Future work should examine differences in fuel moisture of duff layers as well as fine dead surface fuels and stand microclimate characteristics over a wider range of stand structures and composition and in relation to process-based models and drier fuel conditions.

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