

Effect of a Spaced Thinning in Mature Lodgepole Pine on Within-Stand Microclimate and Fine Fuel Moisture Content

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Abstract—Thinning mature forest stands to wide spacing is prescribed to reduce crown bulk density and likelihood of severe crown fire behaviour. However, it may adversely affect surface fuel load, moisture content and within-stand wind, which influence surface fire behaviour and crowning potential. Comparison of a mature lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stand in southeastern British Columbia to an adjacent stand with half the basal area removed by thinning to 4 m inter-tree spacing found a decrease in canopy interception of rainfall and increases in solar radiation, windspeed, and near-surface air temperature during peak fire danger hours over 13 fire seasons. Moisture content of needle litter and fuel moisture sticks was measured in both stands in 2005. Between-treatment differences in moisture content of sticks and litter were greatest after rain, but decreased quickly as fuels dried, to very small at moderate fire danger. Prediction of moisture content of lodgepole pine needle litter using the Canadian Fire Weather Index System also improved as fuels dried and worked well for both stands at moderate fire danger. There was only one day at higher fire danger during the study. Further studies should examine physical models of fuel moisture and microclimate under a wider range of stand densities, fuel types and climatic conditions.

Introduction

Thinning mature forest stands to a wide inter-tree spacing is sometimes prescribed to reduce crown bulk density and lower the likelihood of severe crown fire behaviour (Hirsch and Pengelly 1999). However, thinning may also affect surface fuel loading, fine fuel moisture content and within-stand winds, which in turn affect surface fire behaviour and crowning potential (Rothermel 1983; Scott 1998; Scott and Reinhardt 2001). Rates of wetting or drying, and consequently 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 and solar radiation, and near surface air temperature, relative humidity and within-stand windspeed (Rothermel 1983; Forestry Canada 1992).

The purpose of this paper is to compare and contrast a natural mature lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stand to an adjacent stand which was thinned to uniform 4 m spacing in February 1993, with respect to:

- within-stand microclimate parameters that are likely to affect moisture content of fine surface fuels;

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- measured moisture content of fine surface fuels; and,
- difference between actual moisture content of lodgepole pine needle litter and values predicted by the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987).

Study Area

This study was conducted at one of three sites where, since 1992, researchers from the Canadian Forest Service and Forest Engineering Research Institute of Canada and operations staff from the British Columbia Ministry of Forests and Range have studied the efficacy of commercial thinning to uniform wide spacing for reaching several stand-level management objectives in natural 70 to 100 year old lodgepole pine.

The site is located south of Cranbrook in south-eastern British Columbia at $49^{\circ} 25' N$, $115^{\circ} 36' W$, on level terrain in a broad valley at 1350 m elevation. The overstorey consists of a single cohort lodgepole pine stand that originated after 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 to 20 ha treatment units (fig. 1) was commercially thinned by Galloway Lumber Co. Ltd. to a uniform inter-tree spacing of approximately 4 m, a second was clearcut and the third was left untreated (Mitchell 1994). Stand characteristics are shown in table 1 and the fuel complexes are described in table 2. Sparse understorey vegetation is typical of the lodgepole pine/Oregon grape-pinegrass site series of the dry cool Montane Spruce biogeoclimatic subzone (Braumandl and Curran 1992). Various studies at this site have examined the harvest operations and effects on stand and tree growth, wildlife habitat, and forest health (for example, Mitchell 1994; Allen and White 1997; Safranyik and others 1999; Safranyik and others 2004; Whitehead and others 2004; Whitehead and Russo 2005). This paper examines and discusses selected microclimatic parameters that may affect fuel moisture from the project's 13-year database at the Cranbrook site (1993-2005) and fine fuel moisture content measured in the thinned and unthinned stands during the 2005 fire season.

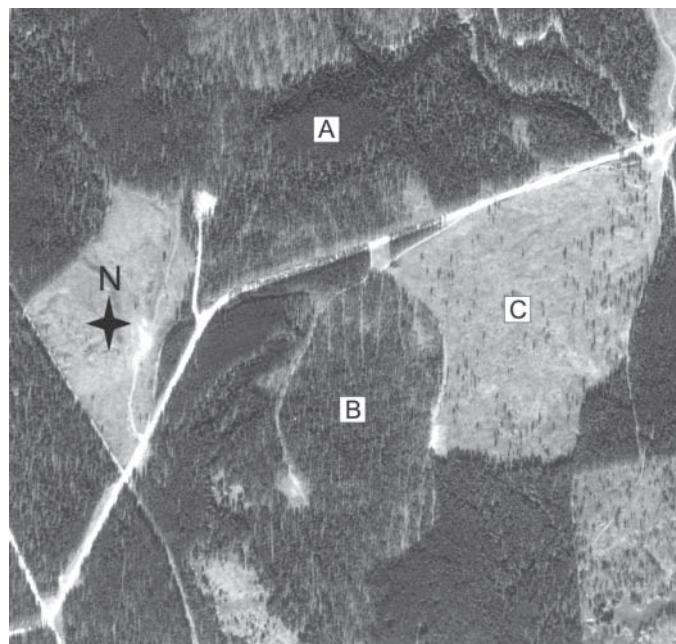


Figure 1—Aerial overview of site with weather station locations represented by letters A (unthinned control), B (thinned to 4 m spacing), and C (clearcut).

Table 1—Distribution of all trees >7.5 cm d.b.h., by 5 cm diameter classes in the unthinned control and thinned stands at the Cranbrook study site.

Stand	Species	Midpoint of diameter class (cm)						
		10	15	20	25	30	35	40
----- trees/ha -----								
Control	W. Larch	8	0	0	0	0	0	0
	L. Pine	208	700	633	125	17	0	0
Thinned	W. Larch	11	5	5	5	5	5	11
	L. Pine	0	11	155	192	53	5	0

Source: Whitehead, R.J.; Brown, B.N.; Nemec, A.F.L.; Stearns-Smith, S.C. (Submitted 2006). Stand and tree-level growth response to spaced commercial thinning and fertilization treatments in mature lodgepole pine stands in southeastern British Columbia. Natural Resources Canada, Canadian Forest Service, Information Report BC-X---.

Table 2—Description of the fuel complexes (July 2005)^a, in the unthinned control and thinned stands at the Cranbrook study site.

Fuel Complex	Control	Thinned
----- Overstory Conifers (7.5+ cm d.b.h.) -----		
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 ^b - 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)	0.02	0.33
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)	0.94	1.06
Duff bulk density (kg/m ³)	113.5	104.9
Duff depth (cm)	2.71	3.22
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

^aSource: Russo, G.L.; Whitehead, R.J. Natural Resources Canada, Canadian Forest Service, unpublished data.

^bBased on foliar weight calculated using equations from Standish and others (1985).

Methods

Microclimate

Weather stations with dataloggers (Campbell Scientific CR-10) were installed in the centre of each treatment unit (at least 125 m from the outside edge) in 1992 (fig. 1). Air temperature and relative humidity (Campbell Scientific HMP 45C) and full spectrum solar radiation (LiCor LI200SZ pyranometer) sensors were mounted on a tower at 1.3 m height and windspeed monitors (RM Young Wind Monitors) at 3 m height. Three air temperature sensors (Campbell Scientific 107B) were also located nearby at 5 cm above the forest floor. Solar radiation and air temperature sensors at 5 cm height were sampled every five minutes, while air temperature at 1.3 m height, relative humidity and windspeed were sampled every minute. Hourly data summaries and 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 in the clearcut treatment unit only until 2003, when gauges were also added in the thinned and unthinned stands. Each rain gauge was mounted at 1.3 m above ground-level and 3 m to 5 m from the sensor tower.

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 nearby Environment Canada station normals, where sensors were not replicated (relative humidity, windspeed, precipitation and solar radiation). 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 Surface Fuels

Fuel Moisture Sticks—Five sets of 10-hour fuel moisture sticks (4-stick arrays of ponderosa pine dowels weighing 100 g), mounted on wire brackets at 20 cm above the forest floor were positioned 2-m apart on an east-west transect (fig. 2) near the weather station in the thinned and control stands. Each array was weighed on site at 16:00 Mountain Standard Time (MST) on 70 days between June 21 and September 25, 2005, and oven dried at the end of the season to determine how much weight was lost due to weathering effects over the season. Moisture content was calculated on each sampling day using equation 1:

$$\text{Moisture Content (\%)} = 100 \times \left(\frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \right) \quad (1)$$

with dry weights adjusted for weathering, using equation 2:

$$\text{Adjusted Dry Weight (g)} = 100 - \left(\frac{100 - a}{b} \right) \times c \quad (2)$$

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

Needle Litter—Ten 1-m² quadrats, spaced 1 m apart on a transect perpendicular to the moisture stick transect, were established in each stand for collection of lodgepole pine needle litter (fig. 3). Cured lodgepole pine needles were collected from the forest floor nearby and distributed in a thin



Figure 2—Five sets of fuel moisture sticks set up in the thinned stand (left) and in the control stand (right).



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).

even layer (<1.5 cm thick) amongst the quadrats on May 18, 2005 to ensure ample litter for sampling throughout the season. Five samples (approximately 50 g each) of needle litter were collected at 16:00 MST, from alternating odd and even quadrats each sampling day, at 16:00 MST on 70 days between June 21 and September 25, 2005. Each sample was placed in a numbered tin and weighed on site to the nearest 0.1g, then oven dried for at least 24 hours at 100°C and re-weighed. Moisture content of needle litter was calculated using equation 1.

Predicted Moisture Content of Needle Litter—In Canada, the codes and indices that make up the Fire Weather Index System are calculated from weather station outputs. On June 24, 2005, the B.C. Ministry of Forests and Range Southeast Fire Centre installed a standard Fire Weather Station (Forest Technology Systems) in the clearcut opening to determine daily fire weather indices, including the Fine Fuel Moisture Code (FFMC) and Fire Danger Class (B.C. Ministry of Forests 1983). FFMC is a numerical index of the moisture content of litter and other cured fine fuels (Van Wagner 1987). We used FFMC to predict moisture content of lodgepole pine needle litter using equation 3 (Van Wagner 1987):

$$\text{Predicted Moisture Content (\%)} = \frac{147.2 \times (101 - \text{FFMC})}{59.5 + \text{FFMC}} \quad (3)$$

Data Analyses

Microclimate—Mean hourly within-stand windspeed, air temperature, total solar radiation, and relative humidity (RH) during peak fire danger hours (12:00 to 16:00 MST) in the control and thinned stand over thirteen fire seasons (1993 to 2005) were compared graphically. Precipitation data over three fire seasons (2003 to 2005) were consolidated into 54 “rain events” (periods of 1 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 ($\alpha = 0.05$).

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

Fine Fuel Moisture Content—The variance was not constant across the range of moisture content data for fuel moisture sticks and lodgepole pine leaf litter. We grouped the data by Fire Danger Class for graphical comparisons and it was clear that this problem was associated with rainfall, which occurred primarily when the Fire Danger Class was Very Low (26 days). During periods when Fire Danger Class was Low (31 days) or Moderate (12 days) variance in the data was small and consistent. We therefore restricted statistical analyses of between-treatment differences to days with Low or Moderate ratings and used two-tailed paired sample t-tests to investigate between treatment differences in moisture content of fuel moisture sticks ($\alpha = 0.05$) and differences in moisture content of lodgepole pine leaf litter between treatments, and between each treatment and values predicted from FFMC with $\alpha = 0.02$ 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, and mean canopy interception was significantly lower ($p < 0.0001$) in the thinned stand (51.1 percent; $SE = \pm 2.9254$) than in the unthinned stand (65.3 percent; $SE = \pm 2.9596$ percent).

Mean hourly within-stand windspeed, air temperature, relative humidity and solar radiation in the thinned stand during peak fire hours (12:00 to 16:00 MST) are plotted against the corresponding hourly means in the untreated control stand in figures 4 to 7, respectively. Windspeed and air temperature were consistently higher in the thinned stand. Although total solar radiation was most often higher in the thinned stand, between-treatment differences were not as consistent as for windspeed and air temperature. This 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. Most between-treatment differences were intuitive, with the exception of relative humidity, where no difference was detectable within sensor error (± 3 percent) when measured at 1.3 m above the forest floor. However, there was also no between-treatment difference in mean air temperatures measured at 1.3 m height, although they were consistently higher in the thinned stand when measured much closer to the surface fuels of interest (at 5 cm height). We did not measure RH at 5 cm and cannot discount the possibility that it may also differ nearer the forest floor.

Daily mean moisture contents of fuel moisture sticks in the thinned stand are plotted against corresponding daily means in the untreated control stand in figure 8, and within Fire Danger Classes 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

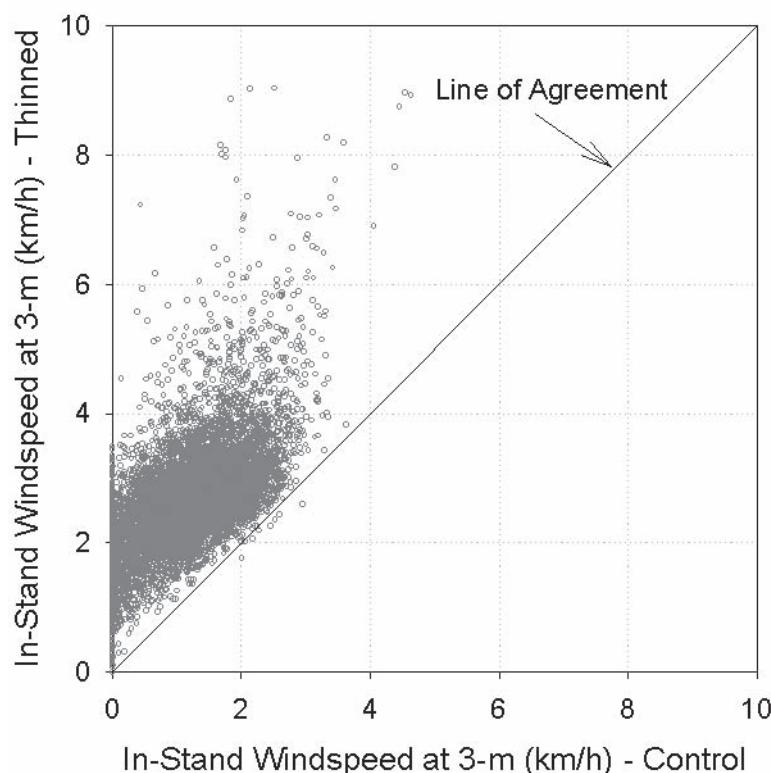


Figure 4—Hourly means of windspeed (km/h) at 3 m height in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding means in the control stand (n=7380 hours).

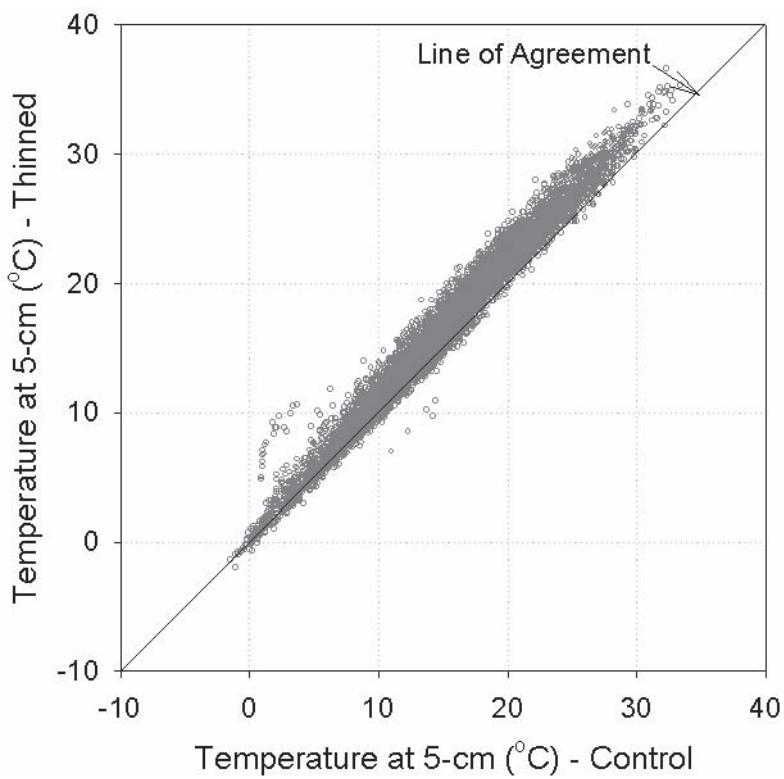


Figure 5—Hourly means of air temperature ($^{\circ}\text{C}$) at 5 cm height above ground in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding means in the control stand (n=7760 hours).

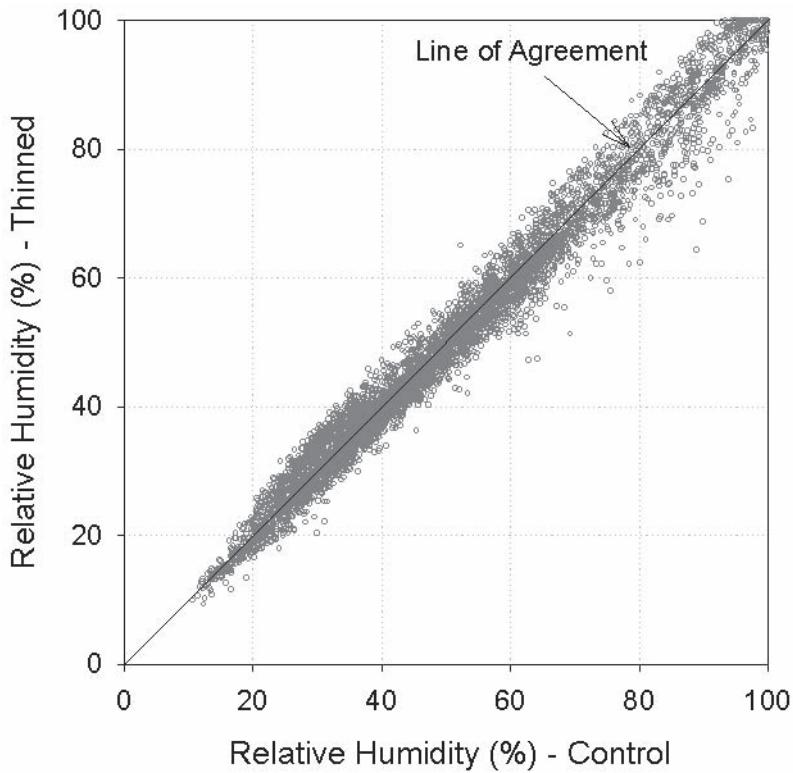


Figure 6—Hourly means of relative humidity (percent) at 1.3 m height in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding means in the control stand (n=5809 hours).

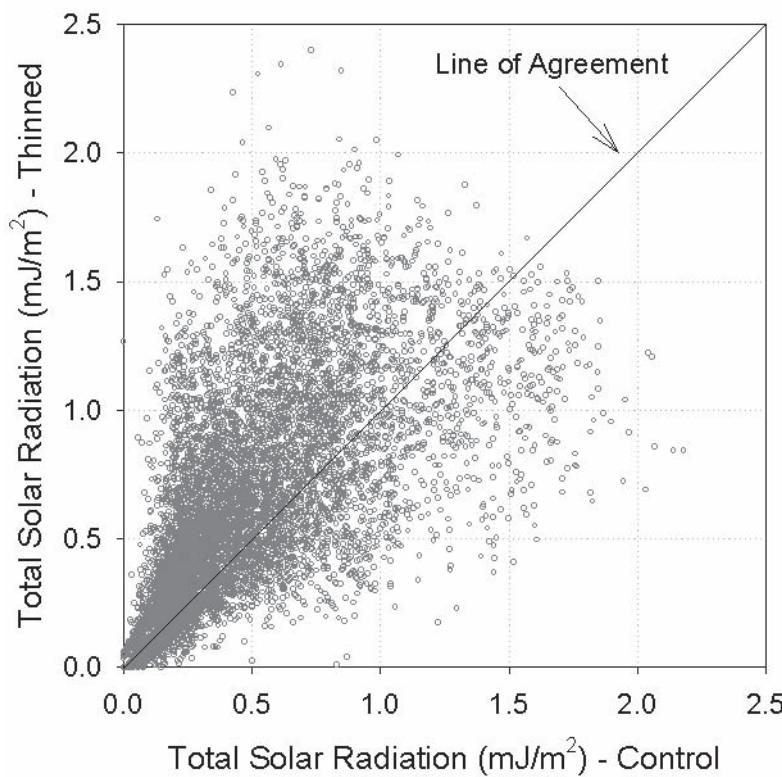


Figure 7—Total hourly solar radiation (mJ/m^2) at 1.3 m height in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding total hourly solar radiation in the control stand ($n=8503$ hours).

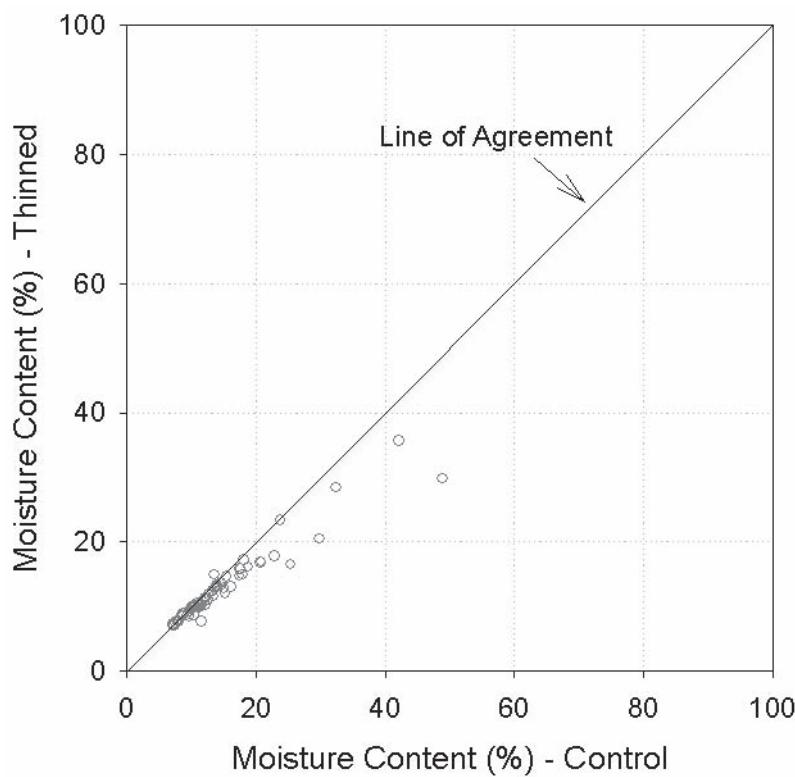


Figure 8—Daily mean moisture content (percent) of fuel moisture sticks at 16:00 MST in thinned and unthinned stands on 70 days between June 21 and September 25, 2005.

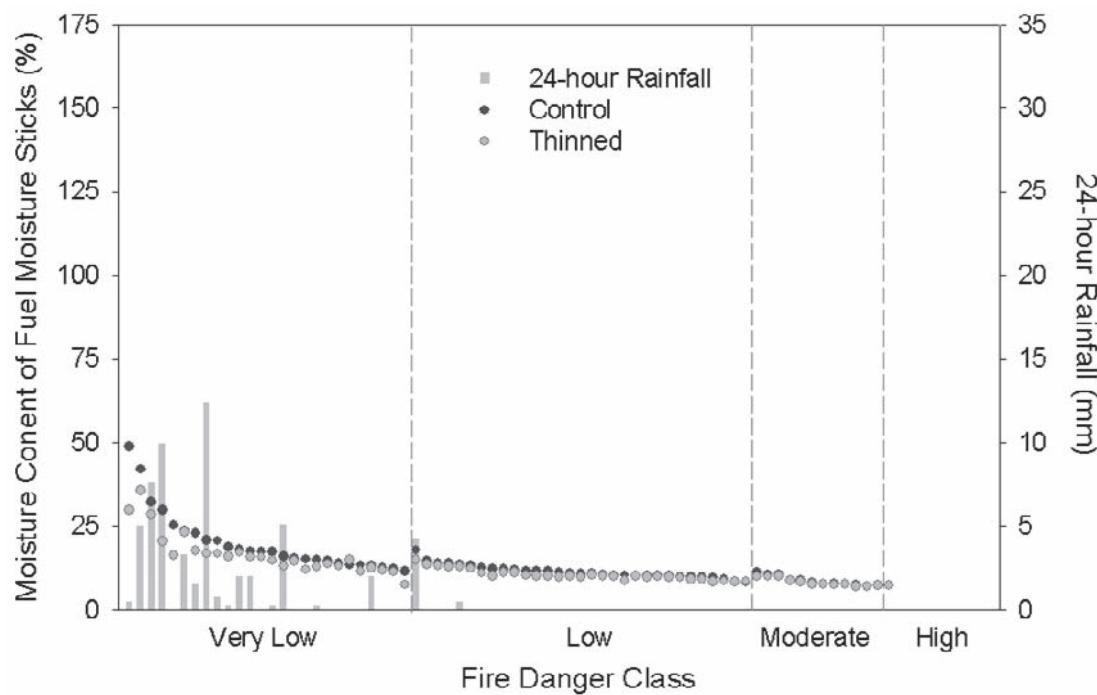


Figure 9—Mean moisture content (percent) of fuel moisture sticks in the thinned and unthinned stands, plotted from wettest to driest control value within different Fire Danger Classes, with corresponding 24-hour rainfall (mm) shown as bars.

about 20 percent and as Fire Danger Class increases (fig. 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 (fig. 10 and fig. 11; table 3). Pook and Gill (1993) compared an untreated radiata pine (*Pinus radiata* D. Don) stand 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 declining moisture content and increasing concern for fire danger.

Table 3—Descriptive statistics (mean, standard deviation and standard error of the mean) for needle litter and fuel moisture stick moisture content at different fire danger classes.

Danger Class		\bar{X}	SD	SE	\bar{X}	SD	SE
Low (n=31)	Control	17.2	7.23	1.30	11.4	1.99	0.36
	Thinned	13.2	3.19	0.57	10.5	1.61	0.29
	Predicted	15.7	6.91	1.24	—	—	—
Moderate (n=12)	Control	10.2	2.91	0.84	8.6	1.40	0.40
	Thinned	8.9	2.19	0.63	8.3	1.18	0.34
	Predicted	9.3	1.96	0.57	—	—	—

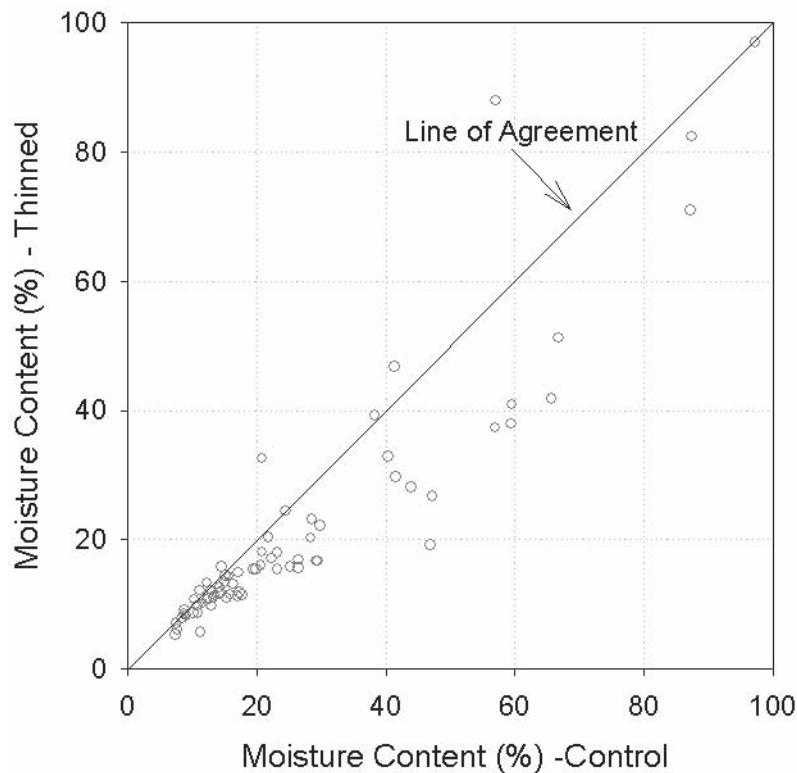


Figure 10—Daily mean moisture content (percent) of lodgepole pine needle litter at 16:00 MST in thinned and unthinned stands on 70 days between June 21 and September 25, 2005.

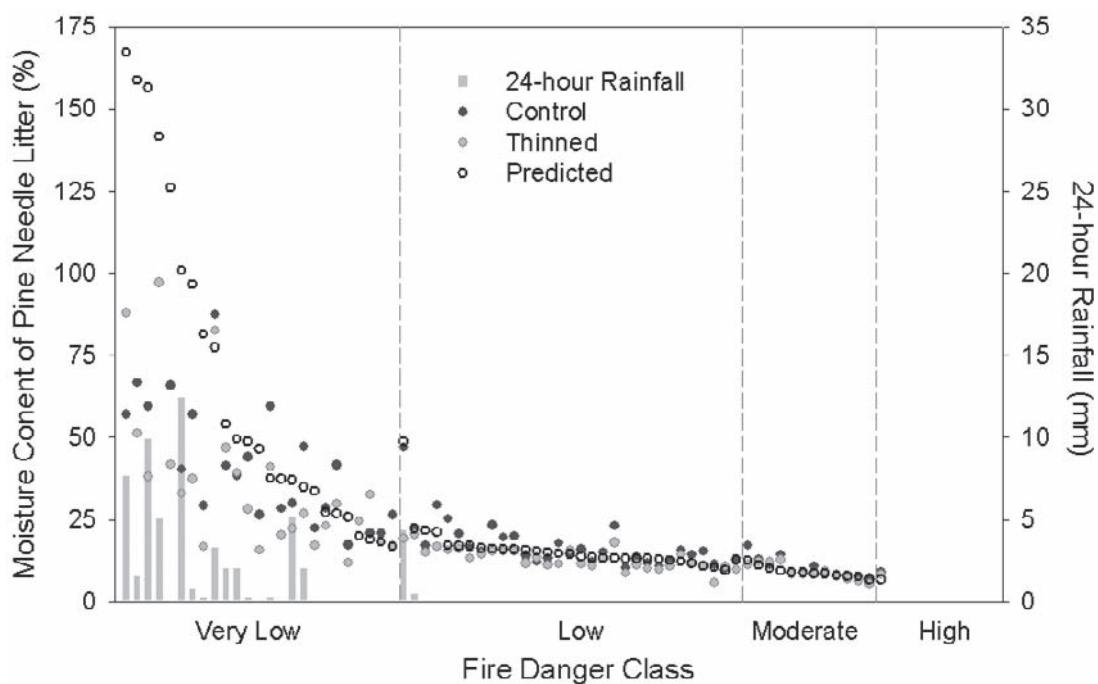


Figure 11—Predicted and actual mean moisture content (percent) of lodgepole pine needle litter in the thinned and unthinned stands, plotted from wettest to driest predicted value within different Fire Danger Classes, with corresponding 24-hour rainfall (mm) shown as bars.

Tanskanen and others (2005) found that canopy characteristics of a mixed Norway spruce (*Picea abies* (L.) Karst) and Scotch 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, windspeed 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 Fire Danger Class was Low, and also for sticks when Danger Class was Moderate (table 4). Although statistically significant, it is unlikely that such small differences in fine surface fuel moisture (for example, 0.3 percent difference in stick moisture content at Moderate fire Danger Class) would have any practical effect on ignition probability or crowning potential. However, there was only one sampling day with a higher fire danger during this study and similar measurements at High and Extreme Fire Danger Classes are recommended to confirm these findings during periods of most concern to fire managers.

Moisture content of fine surface fuels is one important factor used in the Canadian Forest Fire Behaviour Prediction System to model ignition potential (Lawson and others 1994), surface fire intensity and rate of spread (Taylor and others 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). Our measurements of moisture content of needle litter were not significantly different in either treatment from the values predicted from FFMC using Van Wagner's equation, when Fire Danger Class was Low or Moderate, although the values were consistently slightly higher than predicted in the control stand and slightly lower than predicted in the thinned stand (fig. 11; table 3). Predictions of moisture content of needle litter from daily FFMC values improved as fire danger increased (fig. 11) and moisture content was predicted well in both stands when Fire Danger Class was Moderate. FFMC reflects 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 fine fuel moisture content in both stand conditions we studied.

Table 4—Two-tailed p values from paired sample t-tests comparing needle litter moisture content ($\alpha = 0.02$) and fuel moisture stick moisture content ($\alpha = 0.05$).

Danger Class	Control vs. Thinned	Control vs. Predicted	Thinned vs. Predicted	Control vs. Thinned
<i>litter</i>				
Low	0.0003	0.0278	0.0224	<0.0001
Moderate	0.0281	0.0391	0.3021	0.0112

Conclusions

Removing approximately half of the basal area of a mature stand of lodgepole pine in southeastern British Columbia, by thinning from below to uniform 4 m inter-tree spacing, resulted in decreased canopy interception of rainfall and increased within-stand solar radiation, windspeed, and near-surface air temperature. Moisture content of both needle litter and of fuel moisture sticks were most different in thinned and unthinned stands following rainfall, but these differences decreased rapidly as fuels dried. Under moderate fire danger conditions, between-treatment differences were very small and not practically significant. Values for moisture content of lodgepole pine needle litter in both stands were predicted well by the Canadian Fire Weather Index System. Further work is needed to examine physical models of fuel moisture and microclimate under a wider range of stand densities, fuel types and climatic conditions.

Acknowledgments

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