

## Bark temperature patterns in mountain pine beetle susceptible stands of lodgepole pine in the central Rockies

J.M. SCHMID,<sup>1</sup> S.A. MATA, AND R.A. SCHMIDT

USDA Forest Service, Rocky Mountain Forest and Range Experiment Station,  
240 West Prospect, Fort Collins, CO 80526, U.S.A.

Received November 15, 1991

Accepted April 23, 1992

SCHMID, J.M., MATA, S.A., and SCHMIDT, R.A. 1992. Bark temperature patterns in mountain pine beetle susceptible stands of lodgepole pine in the central Rockies. *Can. J. For. Res.* **22**: 1669–1675.

Bark temperatures were recorded on five lodgepole pine (*Pinus contorta* Dougl. ex Loud.) in stands of different growing stock levels in Colorado and Wyoming. Mean bark temperatures were significantly different among growing stock levels. Temperatures in the partially cut growing stock levels were significantly warmer than in uncut controls during diurnal hours, but temperatures were cooler during nocturnal hours. Bark temperatures correlated with ambient air temperature. Equations were developed for predicting north- and south-side bark temperatures for partially cut stands of three growing stock levels and an uncut control from air temperatures. Bark temperature patterns in lodgepole and ponderosa pine (*Pinus ponderosa* Laws.) stands are compared. The relationship between growing stock level and mountain pine beetle (*Dendroctonus ponderosae* Hopk.) infestation is discussed from the standpoint of bark temperatures.

SCHMID, J.M., MATA, S.A., et SCHMIDT, R.A. 1992. Bark temperature patterns in mountain pine beetle susceptible stands of lodgepole pine in the central Rockies. *Can. J. For. Res.* **22** : 1669–1675.

La température de l'écorce a été enregistrée dans cinq peuplements de pin de Murray (*Pinus contorta* Dougl. ex Loud.) contenant différentes quantités de matériel sur pied au Colorado et au Wyoming. La température moyenne de l'écorce était significativement différente selon la quantité de matériel sur pied. Dans les peuplements qui avaient subi une coupe partielle, la température était significativement plus chaude pendant le jour que dans les peuplements témoins qui n'avaient pas été coupés mais elle était plus froide pendant la nuit. La température de l'écorce était corrélée avec la température de l'air ambiant. Des équations capables de prédire la température de l'écorce du côté nord et du côté sud ont été développées à partir de la température de l'air pour des peuplements partiellement coupés à trois niveaux de matériel sur pied et pour des peuplements témoins non coupés. Les patrons de température de l'écorce sont comparés dans des peuplements de pin de Murray et de pin à bois lourd (*Pinus ponderosa* Laws.). La relation entre la quantité de matériel sur pied et les infestations du dendroctone du pin (*Dendroctonus ponderosae* Hopk.) est discutée du point de vue de la température de l'écorce.

[Traduit par la rédaction]

### Introduction

Partial cutting of dense pine stands changes their microclimate and thereby reduces their susceptibility to mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopk.) infestation (Amman *et al.* 1988). The differences in stand temperatures influence MPB behavior either directly by eliciting avoidance of warmer stands (Bartos and Amman 1989) or indirectly through their influence on the dispersion and volatility of MPB aggregating pheromones (Fares *et al.* 1980; Schmitz *et al.* 1989).

Bark temperatures in ponderosa pine (*Pinus ponderosa* Laws.) stands are significantly altered by partial cutting (Schmid *et al.* 1991). Bark temperatures on trees in growing stock levels<sup>2</sup> (GSLs) of 40 and 60 were significantly warmer on clear days than on trees in GSLs of 150 (Schmid *et al.* 1991). Outer bark temperatures of GSL 80 trees were also frequently warmer than on GSL 150 trees but often not different than the GSL 40 or 60 trees. Trees in the GSL 100 were occasionally warmer than GSL 150 trees. North-side bark temperatures were cooler and less variable than south-side temperatures (Schmid *et al.* 1991).

Temperature patterns in lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stands have not been determined for specific

stocking levels. Bartos and Amman (1989) found that thinned stands were warmer than unthinned stands, but their temperatures for thinned stands represented averages for stands in which stand density averaged 94 ft<sup>2</sup> (1 ft<sup>2</sup> = 0.09 m<sup>2</sup>) of basal area per acre. They did not examine the temperature relationships between uncut stands and stands thinned to specific stocking levels.

This paper reports on the outside bark temperature patterns on the north and south sides of trees in partially cut stands of lodgepole pine of specific GSLs as compared with uncut stands. The primary goals were to determine if outside bark temperatures were significantly different among the GSLs, the magnitude and frequency of differences between the partially cut GSLs and an uncut control over a 3- to 4-month period, and their daily pattern throughout a 24-h period.

### Methods

Two sets of GSL plots in lodgepole pine stands representing MPB-susceptible stand conditions were selected for temperature measurements. The Brush Creek plots are on the Medicine Bow National Forest about 19 mi (1 mi = 1.6 km) southeast of Saratoga, Wyoming. The KOA plots are on the Colorado State Forest about 18 mi southeast of Walden, Colorado. Basal area per acre, mean diameter at breast height (DBH), trees per acre, and original GSL for both sets of plots are listed in Table 1.

The Brush Creek plots consist of three 2.5-acre (1 acre = 0.40 ha) plots, partially cut to GSLs of 40, 80, 120, and one uncut 2.5-acre plot serving as a control. The plots range in elevation from 8460 to

<sup>1</sup> Author to whom all correspondence should be addressed.

<sup>2</sup> Growing stock level (GSL) is defined as the residual square feet of basal area when average diameter is  $\geq 10$  in. When average diameter is so small that basal area is not a convenient measure, number of trees is used.

TABLE 1. Stand characteristics of the Brush Creek and KOA growing stock level (GSL) plots

	Basal area per acre (ft <sup>2</sup> )	Mean DBH (in.)	Trees per acre	Original GSL
<b>Brush Creek</b>				
GSL 40	40	9.8	76	250
GSL 80	81	10.0	148	232
GSL 120	116	8.9	263	245
Control	224	8.8	528	234
<b>KOA</b>				
GSL 80	74	8.2	198	156
GSL 100	97	9.0	218	146
GSL 120	114	8.6	288	145
Control	138	7.8	410	155

8480 ft (1 ft = 0.3 m). All the plots have a southwest aspect except the northern one-third of the GSL 120 plot, which has a north northwest aspect. Slope in all plots ranges from 0 to 5% except for the northern one-third of the GSL 120, where slope approaches 10%.

The KOA plots consist of three 2.5-acre plots partially cut to GSLs of 80, 100, and 120, with one uncut 2.5-acre plot serving as the control. The plots are 8820 ft in elevation. Slope in all plots is essentially 0%, and therefore, they have no aspect.

As in the study of ponderosa pine bark temperatures (Schmid *et al.* 1991), bark temperatures at 1.5 m above ground on the north and south sides of five trees on each plot were recorded in degrees Fahrenheit (°F) (Fahrenheit temp. = 1.8(Celsius temp.) + 32) with YSI thermilinear thermistor networks<sup>3</sup> attached to wires that were connected to Campbell Scientific 21× microloggers. The thermistor bead portion of each thermilinear thermistor network was placed in crevices or under bark scales so they were shaded from direct sunlight. Ambient air temperature at 1 m above ground was recorded in the vicinity of each micrologger, which was centrally located in relation to the sample trees.

Temperatures were recorded during May 25 to June 7, June 16 to June 26, and July 25 to August 14, 1990, on the Brush Creek plots and during June 29 to July 14, 1990, on the KOA plots. The MPB generally attacks lodgepole pine from late July to mid-August (Amman and Cole 1983), but beetles have been observed attacking trees the 2nd week in July near Granby, Colorado, which is about 30 m south of the KOA plots (J.M. Schmid, personal observation).

The sample trees were randomly located in the central portion of each plot to reduce possible shading from adjacent uncut areas or from plots of greater tree density. DBH of the sample trees ranged from 7.6 to 12.0 in. (1 in. = 2.54 cm) at Brush Creek and 7.2 to 11.4 in. at KOA.

Instantaneous bark temperatures were recorded every 60 min throughout 24-h periods for several consecutive days. Hereafter, the time when recordings were made (i.e., 06:00, 07:00, etc.) are referred to in the analyses as the time variable. Mountain daylight times (MDT) were recorded on a military time basis to facilitate later analyses.

Initially, north- and south-side bark temperatures from the sample trees were tested across GSLs for significant differences among GSLs and between sides using analysis of repeated measures, with sides and time as repeated measures factors and GSL and nonsuccessive days as analysis of variance factors. However, differences between

sides were inconsistent across time, GSLs, and nonsuccessive days, that is, significant interactions. Therefore, temperatures at specific times (i.e., 08:00, 10:00, etc.) and individual days were compared between north and south sides by deleting the time repeated measures factor from the initial analysis.

Mean bark temperatures were computed for the north side, the south side, and the average of both sides combined on the hour for each hour recorded. For example, mean temperatures were computed for each hour (01:00, 02:00, etc.) throughout the day of July 31. Before testing the means at specific times for significant differences among GSLs, homogeneity of variance was tested using the Levene statistic (Snedecor and Cochran 1980). When variances were homogeneous, the means were tested for significant differences among GSLs on each day temperatures were recorded using one-way analysis of variance. When mean temperatures exhibited significant differences, Tukey's test was used to separate means that differed significantly. When variances were heterogeneous, Welch's test and multiple comparison procedures for data with heterogeneous variance were used to determine significant differences among means (Dunnett 1980; Milliken and Johnson 1984). Significance was tested with  $\alpha = 0.05$ .

After the analyses were completed, the frequency and magnitude of significant differences among GSLs were determined for specific hours within a day by summarizing the results of the individual hourly analyses across days. These frequencies were used to determine the general bark temperature patterns among GSLs.

North-side and south-side temperatures for each GSL at Brush Creek were plotted against air temperature to derive equations for predicting bark temperature on the north and south sides from air temperature. Equations were derived from linear correlations for each side for each GSL for each month of data. One equation was also derived for each side for each GSL for all months combined. The composite equation for each side for each GSL was tested against the individual equations for the respective side for each GSL for each month by using the "extra sum of squares" principle (Draper and Smith 1981) to determine if one equation adequately defined the relationship for the summer months. We did not derive similar equations for the KOA data because we only had data from late June to early July.

## Results and discussion

### Temperature patterns among GSLs

Mean bark temperatures for the combined sides varied significantly among GSLs at each location but were not significantly different between all GSLs for all time periods. The frequency of significant differences in bark temperatures was influenced by GSL, time of day, and weather conditions. Generally, trees in the lower GSLs were warmer than trees in the control during the diurnal hours and cooler during the nocturnal hours (Figs. 1 and 2).

Variances around the means among GSLs were generally homogeneous except at 08:00, 10:00, 16:00, and 18:00. We believe the heterogeneity during these daylight times is caused by the interaction of the sun's angle and stand density such that solar radiation strikes some tree boles in the partially cut stands, especially the lower GSLs, and creates greater variability in their bark temperatures.

The frequency and the magnitude of differences among GSLs varied by location. Differences in mean bark temperatures between the GSLs 80 and 120 and their respective control during June and July were greater at Brush Creek than at KOA (Figs. 1 and 2). Although temperatures were not recorded simultaneously in both locations, and thus differences were mostly due to different weather conditions, we believe stand structure partially accounts for some differences between the two locations. The original GSLs at Brush Creek

<sup>3</sup>The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.

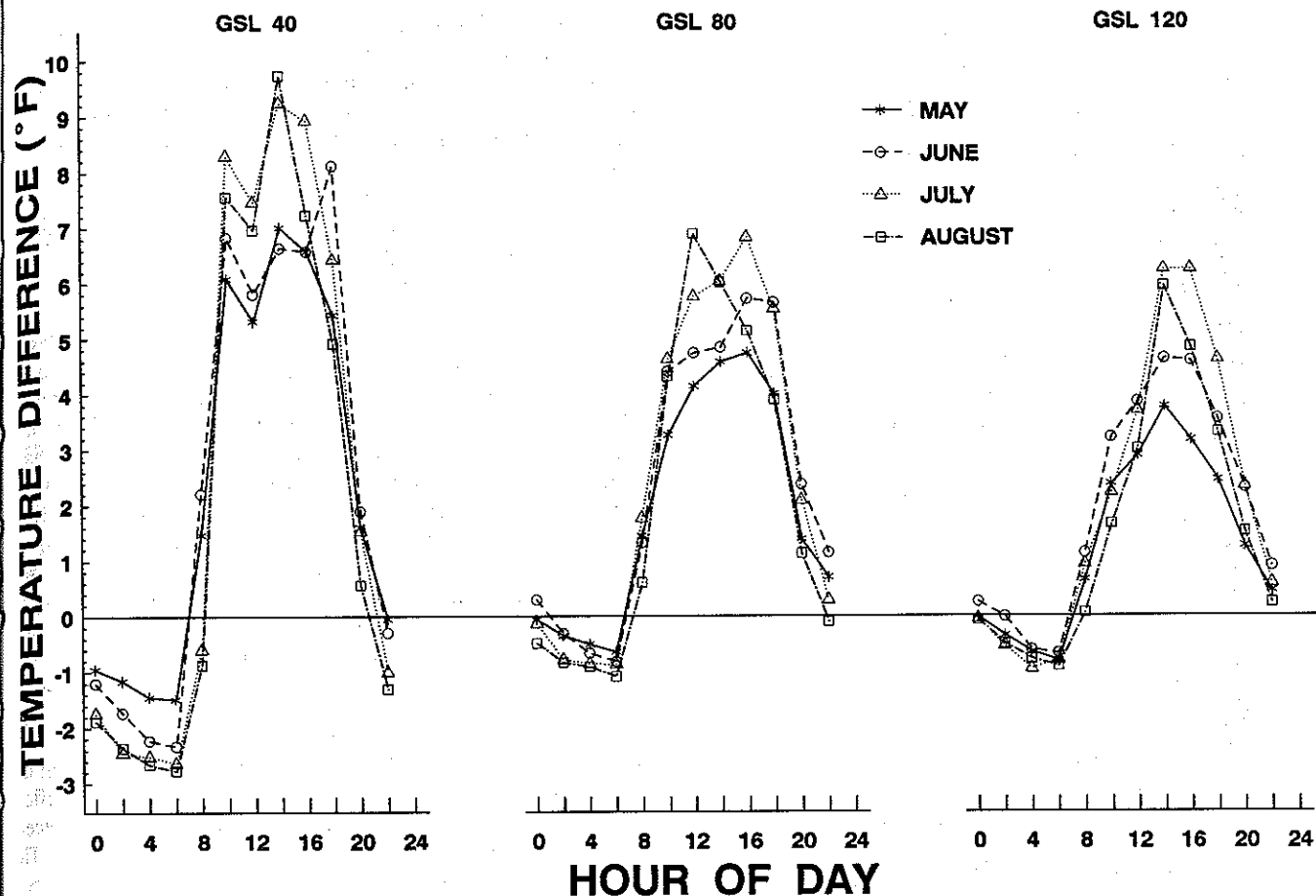


FIG. 1. Mean difference in bark temperatures between growing stock levels (GSL) 40, 80, 120, and their control at Brush Creek by hour of the day for May, June, July, and August. Mean differences equal the mean temperatures of the combined north and south sides in the partially cut plot minus the mean temperatures of the combined north and south sides in the control.

were much higher than at KOA for respective GSLs (Table 1). Consequently, partial cutting removed 16 and 34% more basal area from GSLs 80 and 120 at Brush Creek than from the same GSLs at KOA. Because the partial cutting created more openings in the canopy of the Brush Creek plots than in that of the KOA plots, these openings allowed more solar radiation to penetrate and increased warming of the air and trees in the Brush Creek plots.

Differences in the mean bark temperatures varied with the hour of the day, and the magnitude of these differences during specific hours decreased with increasing GSL. Between 22:00 and 06:00, mean temperatures in the partially cut GSLs were generally at least 1°F cooler than in their controls (Figs. 1 and 2). Only in GSL 40 were temperatures more than 2°F cooler than in the control (Fig. 1). From 07:00 to 10:00, differences in mean bark temperatures between the partially cut GSLs and their controls gradually increased, with increases inversely related to GSL. However, the differences were significant generally less than 30% of the time from May to August.

From 10:00 to 18:00, greater and more frequent differences in mean bark temperatures were particularly evident between the partially cut GSLs and their control at Brush Creek, but these differences varied with GSL and month. The Brush Creek GSL 40 was 5 to 7°F warmer than its control in May–June and 7 to 9°F warmer in July–August (Fig. 1). Tempera-

tures were significantly different from the control about 90% of the time during midday and nearly 100% of the time during 14:00 to 16:00. The Brush Creek GSL 80 bark temperatures were 3.3 to 5.7°F warmer than those in the control in May–June, while in July–August they were 3.9 to 6.9°F warmer. Significant differences occurred about 83% of the time, but only in July were they present more than 90% of the time during the 10:00–18:00 period. Temperatures in GSL 120 were 2.2 to 3.5°F warmer than those in the control in May–June and 1.6 to 6.2°F warmer in July–August. Significant differences occurred 65 to 75% of the time between 10:00 and 18:00; however, temperatures in GSL 120 were different about 35% at 10:00, whereas at 14:00, they were different about 95% of the time.

At the KOA plots, bark temperatures in GSL 80 were 0.5°F cooler than in the control between 02:00 and 06:00, while between 10:00 and 18:00, temperatures averaged less than 1.5°F warmer. However, a malfunctioning micrologger recorded data for only 5 days, so our pattern for this GSL may not be representative. Temperatures were significantly different less than 10% of the time and differed by less than 1°F when GSL 120 was compared with the control.

The temperature patterns among lodgepole GSLs at both locations follow the general trend for bark temperature patterns for ponderosa pine as defined by Schmid *et al.* (1991). Basically, temperatures were relatively equal and not

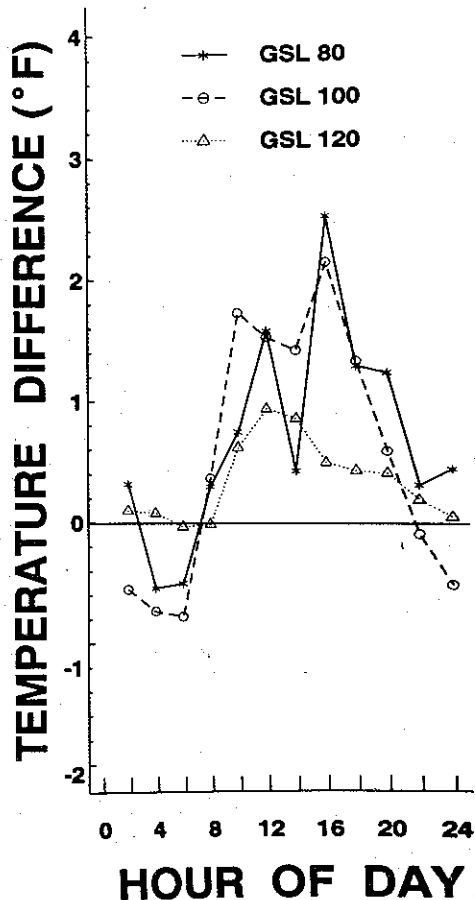


FIG. 2. Mean difference in bark temperatures between growing stock levels (GSL) 80, 100, 120, and their control at KOA by hour of the day for June–July. Mean differences equal the mean temperatures of the combined north and south sides in the partially cut plot minus the mean temperatures of the combined north and south sides in the control.

significantly different from 07:00 to 09:00. As the sun angle increases during these hours, sunlight penetrates the canopies and begins heating the boles, especially in the lower GSLs. Temperatures in all stands increase but the increases are greater in the cut stands. After 09:00, temperatures continue to increase with enough differentiation between the GSLs that significant differences occur more consistently. During midday, temperatures are generally significantly different between GSLs 40 and 80 and the control. GSL 120 may also be significantly different but the frequency is less than in GSLs 40 and 80. As the sun angle declines in the afternoon, temperature differences decrease. Significant differences may still exist between 14:00 and 20:00 because of the bole heating during the midday period. After 20:00, temperatures in the cut stands cool appreciably and become cooler than the uncut control.

The pattern of cooler nighttime bark temperatures in the cut stands, particularly GSL 40, also follows the temperature patterns in ponderosa pine GSLs observed by Schmid *et al.* (1991). Nighttime bark temperatures in GSL 40 were 2 to 3°F cooler than in the control (Fig. 1). In ponderosa pine, nighttime bark temperatures in GSL 40 were 2°F cooler than in

the control and were thought to result from cooler nighttime air temperatures (Schmid *et al.* 1991). Although these low temperatures are probably not significantly different, the difference may reflect the basic difference in ponderosa and lodgepole pine bark thickness. Lodgepole bark is thinner than ponderosa bark, and thinner bark cools faster than thicker bark (Powell 1967). The combination of cooler nighttime air temperatures and greater rate of heat loss on trees with thinner bark may cause the slightly lower bark temperatures in the lodgepole pine GSL 40.

#### Temperature relationships between north and south sides.

The mean north-side bark temperatures were significantly cooler than south-side bark temperatures, but the magnitude of differences and the frequency of significant differences between the two sides varied by the GSL, month, and hour of the day. From 20:00 to 08:00, mean temperatures on the north sides were generally within 1°F of mean temperatures on the south sides for all GSLs during all time periods (Figs. 3 and 4). Temperature differences of this magnitude were significantly different less than 30% of the time in the Brush Creek GSLs 40 and 80 and in all KOA GSLs. However, this temperature difference was significantly different more than 50% of the time in the Brush Creek GSL 120 during specific hours in May and in the Brush Creek control most of the time in June, July, and August. We cannot explain the situation in the Brush Creek GSL 120, but the increased frequency in the significant differences in the Brush Creek control may reflect the movement of cooler air into the plot from an adjacent irrigation ditch that borders the control on the east side. The cool air generally drains into the plot from a southeasterly direction, which may decrease the south-side bark temperatures faster than the north-side temperatures.

Temperature differences between the two sides increased after 08:00 for all GSLs and maximized between 10:00 and 14:00 depending on the GSL (Figs. 3 and 4). Maximum differences for GSLs  $\leq 80$  were evident between 10:00 and 13:00. Maximum differences for GSLs  $\geq 100$  were evident between 12:00 and 14:00.

The greatest differences in north- and south-side bark temperatures were evident in the Brush Creek GSL 40, where differences approached 14°F in July and August (Fig. 3). Maximum differences between the north and south sides for the other Brush Creek GSLs were 7 to 8°F and for the KOA GSLs they were 4 to 6°F (Figs. 3 and 4). During the periods of maximum temperature differences, significant differences within each GSL were more evident in July and August than in May and June.

After 14:00, bark temperature differences between the north and south sides declined to the 1°F temperature difference common to the nocturnal hours. The north-side temperatures in the Brush Creek GSLs 40 and 80 became warmer than the south-side temperatures around 18:00 in May and June. We suspect this late afternoon heating of the north sides of the boles in these months may result because the sun is in a more northerly position.

Bark temperatures correlated with air temperatures (Table 2). The equations reflect the interrelationship of seasonal weather patterns, side of the tree, and GSL.

North-side equations had higher coefficients and lower constants in May and June than in July and August. In May and June, air temperatures are seasonally increasing but cloud

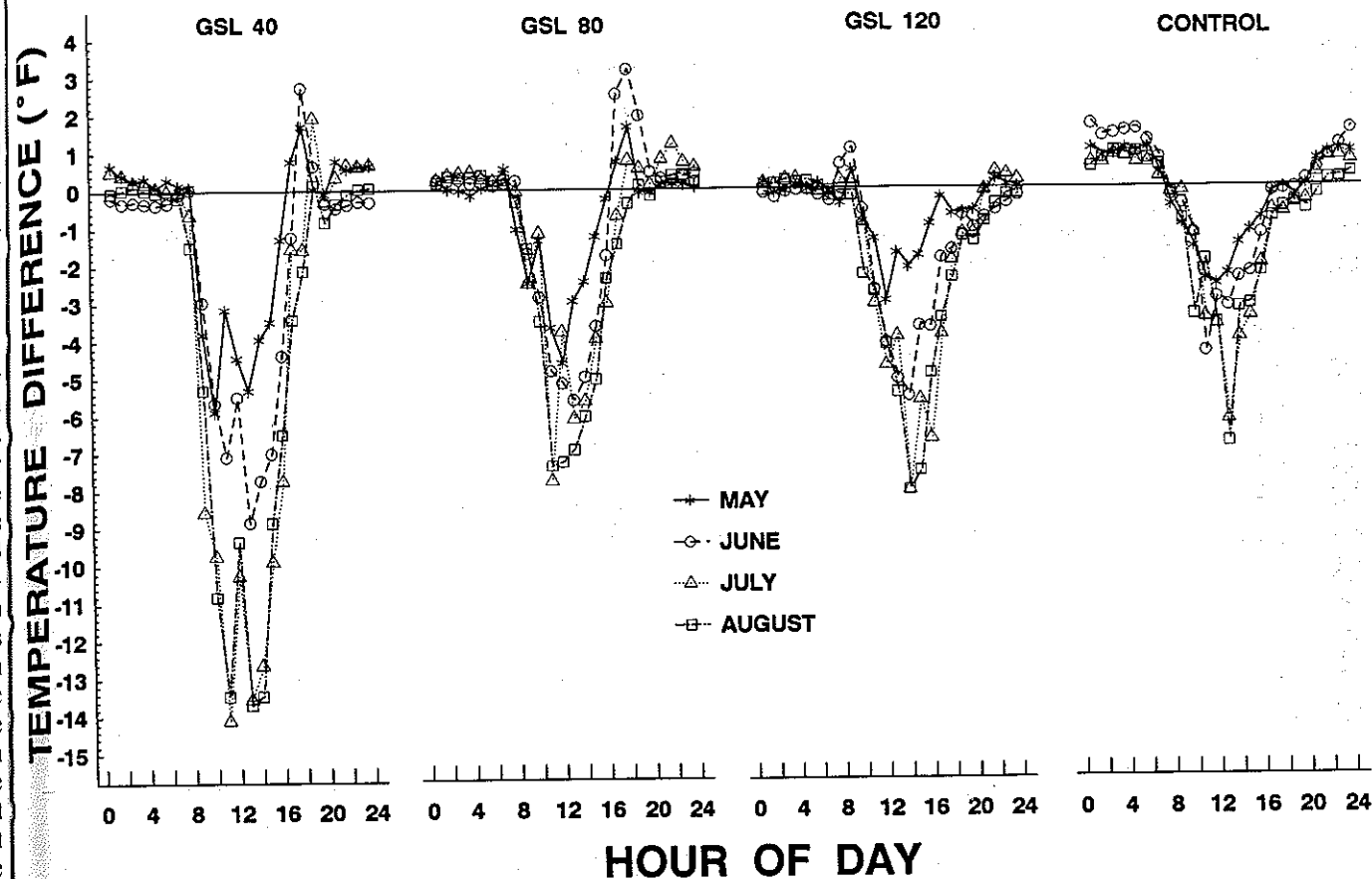


FIG. 3. Mean differences between north and south bark temperatures ( $^{\circ}\text{F}$ ) for each growing stock level (GSL) at Brush Creek by hour of the day, per month. Temperature difference is the north-side temperature minus the south-side temperature, so negative temperatures indicate that the south sides are warmer.

formation from convection heating is rare. When clouds are present, they generally originate from widespread low pressure areas and not from convection heating. In July and August, air temperatures are warmer than in May and June and clouds are frequently formed by convection heating during the day. Because north-side bark surfaces receive little direct sunlight, their temperatures closely follow air temperatures. North-side bark temperature equations in May and June have higher coefficients because hourly air temperatures rarely increase or decrease suddenly. In July and August, air and bark temperatures rise in the morning hours. If convection-formed clouds appear at midday, air temperature drops more rapidly than bark temperature because of the bark's insulating properties. Thus, the relationship between air, and bark temperatures is less precise and the coefficients in the equations are smaller.

South-side equations have more uniform coefficients and constants for most GSLs. Because south-side bark surfaces receive direct sunlight, the coefficients are greater than the coefficients in respective north-side bark temperature equations. The effect of the direct sunlight somewhat mitigates the effect of the seasonal weather patterns and maintains more uniform coefficients for each GSL throughout the 4 months.

The coefficients for the north- and south-side equations generally decrease with increasing stocking level. As stocking level increases, crown closure becomes more complete and

this decreases the chances of bole heating from direct solar radiation. Thus, shading is an important factor and influences the equations relating air and bark temperatures.

#### *Temperature patterns in lodgepole versus ponderosa pine*

Bark temperature patterns in lodgepole pine stands are very similar to the bark temperature patterns in ponderosa pine stands. Maximum temperature differences between comparable GSLs and their controls, and the diurnal pattern of temperature differences, closely agree between the two species. The magnitude of mean temperature differences for the ponderosa pine GSLs in specific months (Schmid *et al.* 1991) is considerably lower than for comparable lodgepole pine GSLs in the same months. These differences are mostly attributable to the weather patterns in 1989 versus 1990 plus the limited number of recording days in the ponderosa pine plots.

Bark temperature patterns for north versus south sides are also very similar to north-south patterns in ponderosa pine.

Original stand structure apparently plays a role in temperature differences between partially cut stands and their respective uncut stands for both species. Temperature differences were slightly greater when stands of high original density were cut to a specific GSL than they were when stands of lower original density were cut to the same GSL. These greater temperature differences are apparently caused by the

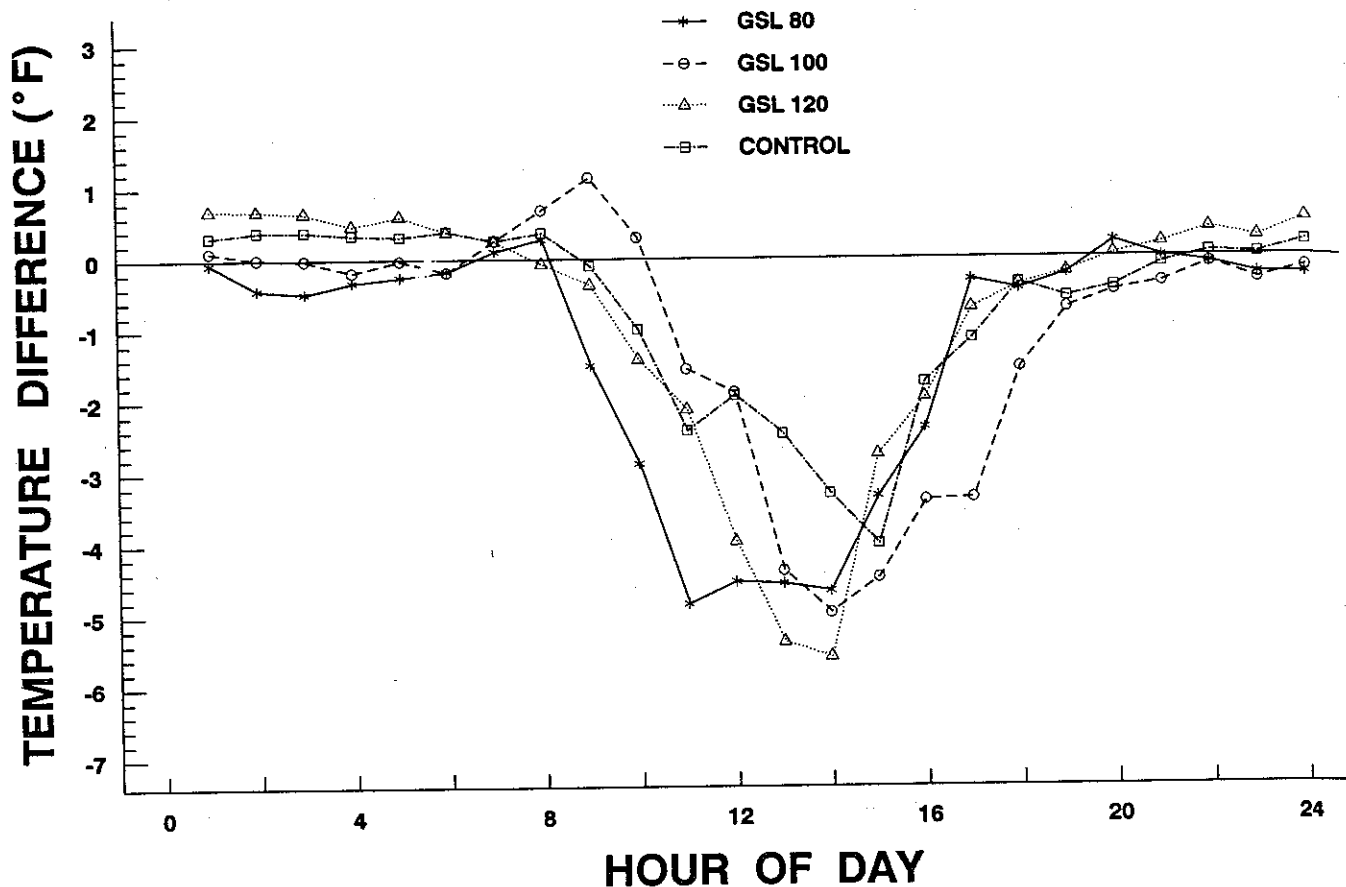


FIG. 4. Mean differences between north and south bark temperatures ( $^{\circ}\text{F}$ ) for each growing stock level (GSL) at KOA by hour of the day for June-July. Temperature difference is the north-side temperature minus the south-side temperature, so negative temperatures indicate that the south sides are warmer.

TABLE 2. Equations depicting the relationship between north-side and south-side bark temperatures and air temperature (AT) for growing stock levels (GSL) at Brush Creek by month

GSL	Month	North-side		South-side	
		Equation	$R^2$	Equation	$R^2$
40	May	$0.94 \text{ AT} + 4.59$	0.96	$1.09 \text{ AT} - 0.94$	0.97
40	June	$0.95 \text{ AT} + 4.14$	0.97	$1.06 \text{ AT} + 0.23$	0.97
40	July	$0.80 \text{ AT} + 11.50$	0.96	$1.12 \text{ AT} - 3.42$	0.97
40	August	$0.82 \text{ AT} + 10.62$	0.97	$1.14 \text{ AT} - 4.60$	0.97
40	All	$0.88 \text{ AT} + 7.27$	0.96	$1.09 \text{ AT} - 1.52$	0.97
80	May	$0.93 \text{ AT} + 5.31$	0.97	$1.00 \text{ AT} + 2.92$	0.97
80	June	$0.99 \text{ AT} + 2.55$	0.99	$1.02 \text{ AT} + 2.10$	0.98
80	July	$0.85 \text{ AT} + 10.35$	0.97	$1.01 \text{ AT} + 2.61$	0.97
80	August	$0.84 \text{ AT} + 10.48$	0.97	$1.03 \text{ AT} + 1.49$	0.96
80	All	$0.90 \text{ AT} + 7.02$	0.98	$1.01 \text{ AT} + 2.34$	0.97
120	May	$0.90 \text{ AT} + 6.39$	0.98	$0.96 \text{ AT} + 4.10$	0.97
120	June	$0.96 \text{ AT} + 4.00$	0.99	$0.99 \text{ AT} - 3.47$	0.98
120	July	$0.79 \text{ AT} + 13.10$	0.97	$0.98 \text{ AT} + 3.52$	0.95
120	August	$0.78 \text{ AT} + 13.19$	0.97	$0.97 \text{ AT} + 4.02$	0.96
120	All	$0.85 \text{ AT} + 8.99$	0.98	$0.98 \text{ AT} + 3.60$	0.97
Control	May	$0.79 \text{ AT} + 10.28$	0.97	$0.90 \text{ AT} + 5.63$	0.97
Control	June	$0.87 \text{ AT} + 7.62$	0.98	$0.93 \text{ AT} + 4.51$	0.98
Control	July	$0.76 \text{ AT} + 14.20$	0.97	$0.93 \text{ AT} + 5.87$	0.96
Control	August	$0.80 \text{ AT} + 12.49$	0.97	$0.94 \text{ AT} + 5.33$	0.95
Control	All	$0.85 \text{ AT} + 8.90$	0.98	$0.94 \text{ AT} + 4.33$	0.97

difference in crown development in the high- versus low-density stands and the relative amount of bole shading after the stands are cut.

*Temperature differences, GSL, and MPB infestations*

Ponderosa pine stands of GSL 100 may be the lowest stocking level where stand temperatures are conducive for MPB attack (Schmid *et al.* 1991). Because temperature patterns in lodgepole pine stands with the same stocking levels are similar to those in ponderosa pine, GSL 100 may also be the threshold density for MPB attack in lodgepole pine stands. However, the temperature patterns in our GSL 80 to 120 lodgepole stands were infrequently different statistically, with maximum mean differences of 2 to 4°F during July–August when MPB attack. This suggests that if GSL 80 stands are not susceptible, then GSL 100 and 120 stands would also be unsusceptible from the temperature standpoint. As noted earlier, uncut lodgepole pine stands frequently exhibit higher stocking densities, which limit crown development. When they are cut, more of the canopy is removed and greater bole heating is possible. Thus, in lodgepole pine stands, GSL 120 may be the lowest level where stand temperatures conducive for attack are found.

Amman, G.D., and Cole, W.E. 1983. Mountain pine beetle dynamics in lodgepole pine forests. Part II: population dynamics. USDA For. Serv. Gen. Tech. Rep. INT-145.

- Amman, G.D., McGregor, M.D., Schmitz, R.F., and Oakes, R.D. 1988. Susceptibility of lodgepole pine to infestation by mountain pine beetles following partial cutting of stands. *Can. J. For. Res.* **18**: 688–695.
- Bartos, D.L., and Amman, G.D. 1989. Microclimate: an alternative to tree vigor as a basis for mountain beetle infestations. USDA For. Serv. Res. Pap. INT-400.
- Draper, N.R., and Smith, H. 1981. Applied regression analysis. 2nd ed. John Wiley & Sons, New York.
- Dunnnett, C.W. 1980. Pairwise multiple comparisons in the unequal variance case. *J. Am. Stat. Assoc.* **75**: 796–800.
- Fares, Y., Sharpe, P.J.H., and Magnuson, C.E. 1980. Pheromone dispersion in forests. *J. Theor. Biol.* **84**: 335–359.
- Milliken, G.A., and Johnson, D.E. 1984. Analysis of messy data. Volume I: designed experiments. Lifetime Learning Publications, Belmont, Calif.
- Powell, J.M. 1967. A study of habitat temperatures of the bark beetle *Dendroctonus ponderosae* Hopkins in lodgepole pine. *Agric. Meteorol.* **4**: 189–201.
- Schmid, J.M., Mata, S.A., and Schmidt, R.A. 1991. Bark temperature patterns in ponderosa pine stands and their possible effects on mountain pine beetle behavior. *Can. J. For. Res.* **21**: 1439–1446.
- Schmitz, R.F., McGregor, M.D., Amman, G.D., and Oakes, R.D. 1989. Effect of partial cutting treatments of lodgepole pine stands on the abundance and behavior of flying mountain pine beetles. *Can. J. For. Res.* **19**: 566–574.
- Snedecor, G.W., and Cochran, W.G. 1980. Statistical methods. 7th ed. The Iowa State University Press, Ames.