Bark temperature patterns in ponderosa pine stands and their possible effects on mountain pine beetle behavior

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Bark temperatures on the north and south sides of five ponderosa pines (*Pinus ponderosa* Laws.) in each of four growing stock levels in two areas in the Black Hills of South Dakota were monitored periodically from May through August 1989. Temperatures were significantly different among growing stock levels and between sides of the tree. The magnitude of differences between the mean bark temperatures in partially cut stands and uncut controls was inversely related to stocking level. Maximum differences in mean bark temperatures among the growing stock levels occurred between 10:00 and 14:00, when differences between the lower growing stock levels and the controls reached 9 to 10°F (Fahrenheit temp. = 1.8(Celsius temp.) + 32). Diurnal differences were greatly influenced by the amount of cloud cover. Nocturnal temperatures generally differed by 1 to 2°F. North-side temperatures were cooler and less variable than south-side temperatures. Temperature relationships and mountain pine beetle (*Dendroctonus ponderosae* Hopk.) behavior are discussed.

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La température de l'écorce du côté nord et du côté sud a été mesurée périodiquement du mois de mai au mois d'août 1989 chez cinq pins à bois lourd (*Pinus ponderosa* Laws.) dans des peuplements de quatre densités différentes à deux endroits dans les Black Hills du Dakota du Sud. La température différait significativement selon la densité et le côté de l'arbre. L'ampleur des différences dans la température moyenne de l'écorce entre les peuplements qui avaient subi une coupe partielle et les peuplements témoins non éclaircis était inversement proportionnelle à la densité. La plus forte différence dans la température moyenne de l'écorce entre les peuplements de densités différentes est survenue entre 10:00 et 14:00 alors que les différences entre la densité la plus faible et le témoin a atteint 9 à 10°F (temp. en Fahrenheit = 1.8(temp. en Celsius) + 32). Les différences diurnes étaient fortement influencées par l'intensité du couvert de nuages. Les températures nocturnes différaient généralement de 1 à 2°F. La température du côté nord était plus basse et moins variable que du côté sud. La discussion porte sur la relation entre la température et le comportement du dendroctone du pin (*Dendroctonus ponderosae* Hopk.).

[Traduit par la rédaction]

Silvicultural treatment of pine stands suceptible to mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopk.) infestation has shown promise in reducing MPB-caused mortality. The first experimental treatments reduced mortality by removing trees greater than 10 in. (1 in. = 2.54 cm) in diameter at breast height (Cole and Cahill 1976; Hamel 1978). More recent management prescriptions emphasized leaving susceptible-sized[2] but evenly spaced trees (McGregor et al. 1987) at various stocking levels on different sites (Schmid 1987). The residual trees are selected for their crown characteristics and spacing as well as their apparent health. These recent partial cuts yielded reduced mortality equal to that in treatments wherein essentially all susceptible trees were removed (McGregor et al. 1987).

One hypothesis explaining the success of partial cutting emphasizes microclimatic changes as the main reason for reduced MPB infestation of the residual trees in partially cut stands (Amman et al. 1988). Differences in stand temperatures influence beetle behavior either directly by eliciting avoidance of thinned stands because they are warmer (Bartos and Amman 1989) or indirectly through the influence of warmer temperatures on the dispersion and activity of MPB aggregating pheromones (Fares et al. 1980; Schmitz et al. 1989). However, the relative importance of changes in air and bark temperatures on either MPB tree selection or MPB aggregation is still unknown.

Air temperatures within the forest are influenced by stand density (Spurr and Barnes 1980). Daytime temperatures are usually warmer in sparsely stocked stands than in dense stands because sparsely stocked stands allow more penetration of solar radiation. However, daytime air temperatures may be warmer in dense stands because they reduce air movement. In contrast, nocturnal temperatures in dense stands may be warmer than in sparsely stocked stands because canopy closure of the dense stands tends to reduce nocturnal radiation losses (Spurr and Barnes 1980).

Although general relationships between stand density and temperature patterns are known, the magnitude of temperature differences among susceptible-sized stands of various growing-stock levels (GSLs) is unknown. Thinned stands of lodgepole pine (*Pinus contorta* Dougl. ex Loud) averaging 94 ft^2 per acre (1 ft^2 = 0.09 m^2; 1 acre = 0.40 ha) were warmer than unthinned stands of 157 ft^2 per acre (Bartos and Amman 1989). Similar information for lodgepole pine stands from other areas or for ponderosa pine (*Pinus ponderosa* Laws.) stands is lacking. Further, information regarding the relative microclimatic relationships among commonly prescribed GSLs is not available. In this study, we compared the outside bark temperature patterns on the north and south sides of trees in partially cut stands of

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[2] Susceptible sized is defined as host trees with a diameter at breast height ≥ 8 in.

various GSLs[3] with an uncut stand. The primary goal was to determine if bark temperature patterns were consistently, and significantly different among the GSLs.

Methods

Two sets of GSL plots on the Black Hills National Forest were selected for temperature measurements. The Brownsville plots and the Black Hills Experimental Forest (hereafter referred to as the Experimental Forest) plots are located approximately 9 and 15 m (1 mi = 1.6 km) south of Lead, South Dakota. Topographically, the plots lie on the central crystalline area (see Boldt and Van Deusen 1974) at elevations of 5720 and 5860 ft (1 ft = 0.3 m), respectively. The plots are essentially pure ponderosa pine, with rare occurrences of paper birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.), and white spruce (*Picea glauca* (Moench) Voss).

The Brownsville plots consist of three 2.5-acre plots partially cut to GSLs of 60, 80, 100 and one uncut 2.5-acre plot serving as a control (GSL 146). The plots are arranged in a square. Plot aspect is generally northerly. Slope varies from 0 to 8% and, therefore, parts of the plots have no slope or aspect.

The Experimental Forest plots consist of three 2.5-acre plots partially cut to GSLs of 40, 80, 100 and one uncut 2.5-acre control plot (GSL 161). The plots are aligned in a row along a contour. Each plot has a east northeast aspect and slope varies between 5 and 10%.

Basal area per acre, mean diameter at breast height, and number of trees per acre for each plot are listed in Table 1. Trees on the Experimental Forest plots are, on average, smaller than those on the Brownsville plots, and therefore, the number of trees per acre in each respective GSL is greater on the Experimental Forest plots.

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 (Fahrenheit temp. = 1.8(Celsius temp.) + 32). Temperatures were recorded via YSI thermilinear thermistor networks[4] attached to wires that were connected to Campbell Scientific 21X microloggers. The thermistor bead portion of each thermilinear thermistor network was placed in a crevice or under a bark scale so it was shaded from direct sunlight. The sample trees were randomly selected in the central portion of each plot to reduce possible shading from adjacent uncut areas or plots of greater tree density. Ambient air temperature at 1 m above ground was recorded in the vicinity of the micrologger, which was centrally located in relation to the sample trees.

Instantaneous bark temperatures were recorded every 60 min during May 16–21, June 27–28, July 21–24, and August 18–25, 1989, on the Brownsville plots and during May 21–23, June 19–26, July 10–21, and August 14–18, 1989, on the Experimental Forest plots. Because the instrumentation was installed and disassembled on the beginning and ending dates of each period, respectively, temperatures were not recorded throughout the 24 h of those days. Hereafter, the times when recordings were made (i.e., 07:00, 08:00, etc., mountain daylight time) are referred to in the analyses as the time variable.

Bark temperatures on the Brownsville plots were also recorded in 1987 and 1988. However, because a full complement of four microloggers was not usually available, temperatures were only recorded on two or three plots at any one time.

TABLE 1. Stand characteristics of the Brownsville and Experimental Forest growing stock level (GSL) plots

	Basal area per acre (ft^2)	Mean diameter (in.)	No. of trees per acre
Brownsville			
GSL 60	60	12.4	71
GSL 80	80	11.5	110
GSL 100	100	12.8	112
Control (GSL 146)	146	12.7	165
Experimental Forest			
GSL 40	40	10.9	62
GSL 80	80	10.9	124
GSL 100	99	9.2	212
Control (GSL 161)	153	8.7	368

Mean bark temperatures were computed for north sides, south sides, and the average of both sides on the hour for each hour recorded. For example, mean temperatures were computed for each hour, 01:00, 02:00, 03:00, etc., throughout the day of July 11. 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 (they usually were), the hourly means were tested for significant differences among GSLs using one-way analysis of variance. When mean temperatures exhibited significant differences, Tukey's test was used to determine which means were different. 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).

Initially, north and south bark temperatures were tested across GSLs for significant differences 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 (i.e., significant interactions). Therefore, hourly temperatures at specific times were compared between north and south sides by deleting the time repeated measures factor from the initial analysis. All tests of significance were tested with $\alpha = 0.05$.

Because only one air temperature measurement was recorded each time the 10 bark temperatures in each GSL were recorded, air temperatures were tested for significant differences among GSLs using analysis of variance with time as a repeated measure, and GSL and nonsuccessive days as analysis of variance factors.

Results and discussion

Mean bark temperatures

The average bark temperatures for the combined north and south sides were significantly different among GSLs at both Brownsville and the Experimental Forest. Both the magnitude of differences in bark temperatures and the frequency of significant differences in mean temperatures between the partially cut GSLs and their respective controls varied by the GSL, month, day and hour of day. However, both the magnitude and the frequency for June and July at Brownsville and in May at the Experimental Forest may

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[3] Growing-stock level (GSL) is defined as the residual square feet of basal area when average diameter is ≥10 in. (Alexander and Edminster 1980). When average diameter is so small that basal area is not a convenient measure, number of trees is used (Myers 1967). See Table 1 for comparison of GSL and basal area when the average diameter is less than 10 in.

[4] 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.

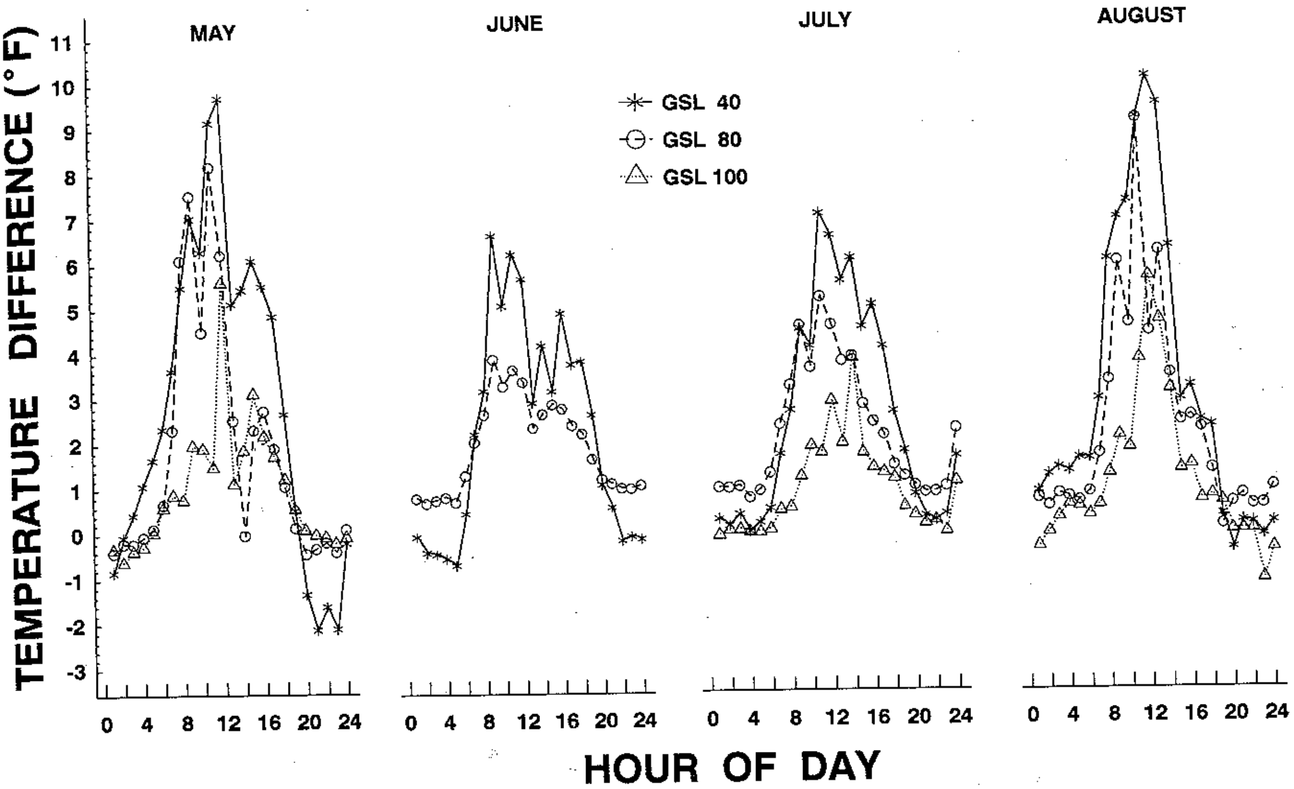

FIG. 1. Mean difference in bark temperatures between the partial-cut growing stock levels (GSL) and the control for the Experimental Forest plots by month and hour of the day. Temperature difference is the temperature in the cut plot minus the temperature in the control plot.

not be representative of the average condition because temperatures were recorded for less than 3 days.

The magnitude of differences between mean bark temperatures in the partially cut GSLs and the uncut control exhibited several patterns. Generally, mean temperature differences were inversely related to GSL, that is, the greatest differences were evident in the lowest GSLs (Figs. 1 and 2). This pattern was distinct in the Experimental Forest plots but was only distinct in August in the Brownsville plots. We believe the presence of clouds during the short periods of record probably prevented the development of maximum differences and clearer differentation between GSLs at the Brownsville site.

Mean bark temperature differences were greatest in May and August in the Experimental Forest plots and in August in the Brownsville plots. The differences again reflected the weather patterns existing during the recording periods. There were a number of rainy days during the June and July recording periods, which tended to reduce maximum differences in the Experimental Forest plots. For the Brownsville plots, similar weather patterns coupled with the low number of recording days in the first 3 months probably prevented greater amplitude in the differences.

The daily pattern of bark temperature differences was similar for the GSLs at both locations. Between 19:00 and 07:00, nocturnal bark temperatures in the partially cut GSLs generally differed from the controls by less than 1°F in all months (Figs. 1 and 2). As air temperatures increased in the morning (07:00–10:00), the magnitude of bark temperature differences increased; the increase being greater in the lower GSLs. Maximum differences were generally evident between 10:00 and 14:00, but the actual hour varied from day to day depending on the cloud cover. Mean bark temperatures in the GSL 40 plot were 9 to 10°F greater than in the control in the Experimental Forest plots during midday (Fig. 1). Bark temperatures in the GSL 80 plots averaged 5 to 8°F greater than their respective controls except in the first 3 months at Brownsville, where cloudy weather prevented higher temperatures. Maximum mean temperatures in the GSL 100 plots were briefly more than 5°F warmer than the controls, but were generally less than 4°F different. After 14:00, mean bark temperature differences declined from their maximum values to the ±1°F nocturnal values.

These daily bark temperature patterns result from differences in stand density among the GSLs. As the sun angle increases during the morning hours, sunlight penetrating the canopies more often heats the boles of the trees in the lower GSLs (40 and 60) than in the higher GSL (control). This creates greater bark temperatures in trees in the lower GSL. As the sun approaches the zenith, solar radiation penetrates even the densest stands (control) so that some tree boles in even the densest stands are heated. During midday, 11:00 to 14:00, maximum differences develop unless clouds are present. After 14:00, the decreasing sun angle again increases the shading of the boles by the tree crowns, particularly in the densest stands. Bark cooling is thus more pronounced in the dense stands, whereas the more open stands (GSLs 40–60) still allow solar radiation penetration and their bark temperatures remain warmer. This creates the significantly warmer temperatures in the afternoon in the lower GSLs.

Bark temperatures in some partial-cut GSLs were occasionally significantly cooler than their controls during nocturnal hours. In the Brownsville plots, mean temperature in the GSL 100 trees was significantly less than the control

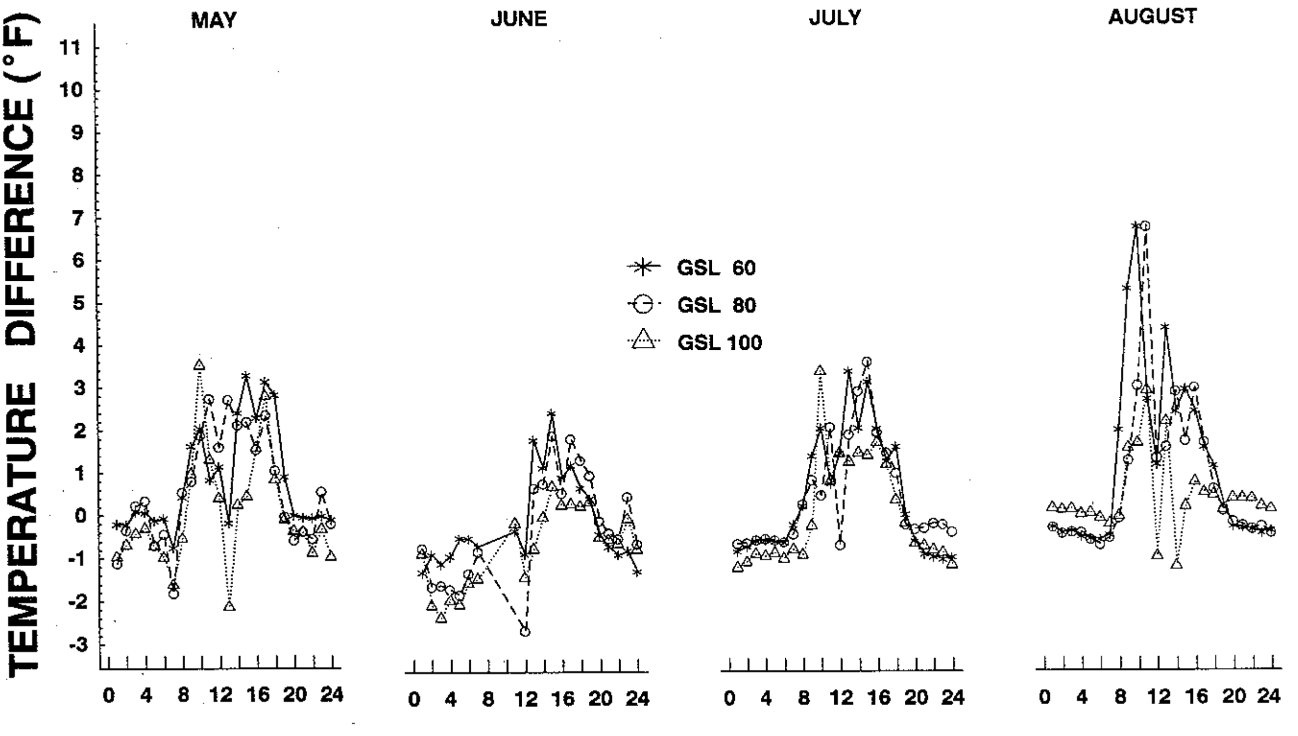

FIG. 2. Mean difference in bark temperatures between the partial-cut growing stock levels (GSL) and the control for the Brownsville plots by month and hour of the day. Temperature difference is the temperature in the cut plot minus the temperature in the control plot.

trees occasionally in 1988 and 1989 (Fig. 2). Because this plot was slightly lower in elevation than the control, cold air drainage into the GSL plot probably created this difference. In the Experimental Forest plots, the GSL 40 trees were cooler than the control trees between 19:00 and 24:00 in May (Fig. 1). Because bark temperatures are strongly influenced by air temperatures (J.M. Schmid, unpublished data) and air temperatures were cooler in the GSL 40 plot, the bark temperatures in the GSL 40 plot became cooler. Nighttime air temperatures in the control were moderated by the greater stand density. The lower stand density in the GSL 40 plot allowed more thermal reradiation out of the canopy; thus cooling air temperatures.

The frequency of significant differences between mean bark temperatures in the partially cut GSLs and the controls was highly variable because of weather conditions and limited data for some months. Despite the limited data, some general trends were evident. Significant differences were more frequent in the lower GSLs (40–80) than in the highest GSL (100). Significant differences during daylight hours were more frequent during recording periods when cloud cover was absent or scattered. Significant differences were more frequent during daylight hours than during nocturnal periods.

Although the daily pattern of significant differences somewhat followed the pattern of mean temperature differences, the pattern was modified by the presence of clouds. On clear days, significant differences developed first between GSLs 40–60 and the controls during 07:00 to 08:00. During the next 2 h, significant differences developed between the other GSLs and the controls. Significant differences remained evident throughout midday until late afternoon, when the pattern reversed itself. If clouds formed during midday and then dissipated around 15:00, temperature differences were significant in the morning hours, not significant during midday, and then significant again in late afternoon. If clouds formed during midday and skies remained cloudy the remainder of the daylight hours, temperature differences were usually significantly different only in the morning hours. When these different patterns are combined and the frequency of significant differences is derived, it is easily understood why the resulting frequencies were so highly variable.

Temperature patterns at the Experimental Forest were significantly different more often during nocturnal and diurnal hours as well as among the GSLs than at Brownsville. Most of the difference in temperature patterns between the two locations was a consequence of different weather patterns during the recording periods. However, part of the difference also resulted from differences in tree size, tree numbers, and our sampling design. Trees in the Brownsville area are larger in diameter on average than trees in the Experimental Forest (Table 1) so that their crowns should be larger. Larger crowns increase the probability that some boles, even in the sparser GSLs, will be shaded for part of the day while most are exposed to direct sunlight. Within our sample of five trees in each GSL, at least one tree exhibited greater or lower temperatures during the midday hours than the other four trees. For example, one GSL 60 sample tree at Brownsville was shaded, so its bark temperature was lower than the other four sample trees. Similarly, one tree in the Brownsville control received solar radiation and consequently had a greater temperature than its neighbors. This situation created enough variation around the respective means that significant differences among the GSLs were detected less often. On the Experimental Forest plots, trees

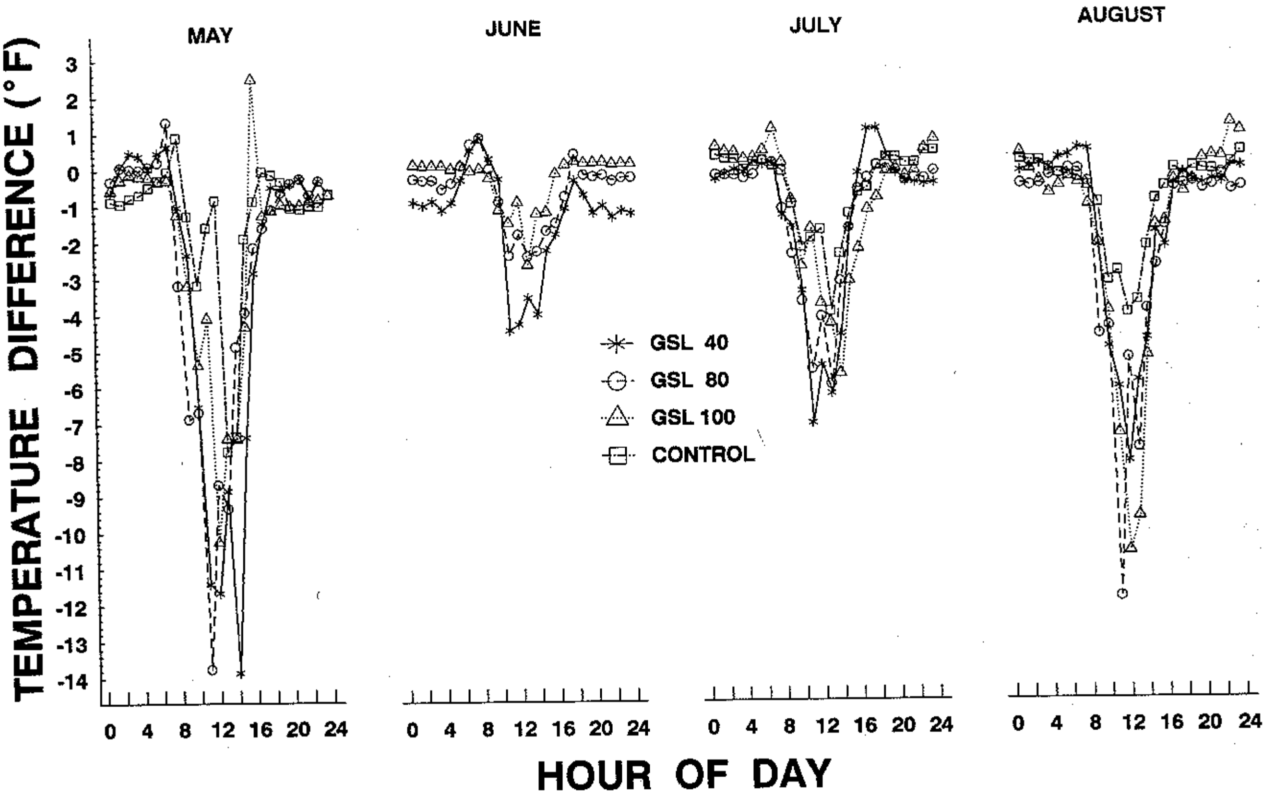

FIG. 3. Mean differences between north and south bark temperatures (°F) for each growing stock level (GSL) at the Experimental Forest by month and hour of the day. Temperature difference is the north-side temperature minus the south-side temperature. Negative temperatures indicate that south sides are warmer.

were smaller in diameter and crown width, such that the variation in bark temperatures within respective GSLs was less. Therefore, the detection of significant differences among GSLs was greater.

Air temperatures

Air temperatures differed significantly among GSLs, dates, and hours of the day. Significant differences among dates and hours, which were expected, resulted from different weather patterns and the intensity of solar radiation, respectively. Because air temperatures differed among GSLs, and are therefore influenced by stand density, equations for predicting bark temperatures in all GSLs from one specific air temperature will require longer, more continuous data than we currently have.

North-side versus south-side bark temperatures

Mean north-side temperatures were significantly cooler than mean south-side temperatures during every hour of the day at both locations. The frequency of significant differences within each GSL was highly variable for the same reasons cited for mean temperatures (i.e., weather patterns and stand density). At times, mean differences of 1 to 2°F were significant, while at other times mean differences of 5°F were not.

Temperature differences between the two sides exhibited similar daily patterns for all GSLs during each of the 4 months (Figs. 3 and 4). The magnitude of maximum temperature differences between north and south sides was fairly uniform among GSLs, with GSLs $\leq$ 80 tending to have the greatest differences. The GSL 100 plot at Brownsville (Fig. 4) was an anomalous condition created because temperatures were recorded for only 1 day. It indicates the magnitude of differences created on clear days. It also indicates that mean temperatures do not reflect maximum differences because they represent the average of temperatures from cloudy as well as sunny days.

The magnitude of the differences among GSLs was greater on the south side during midday than on the north side (Fig. 5), but the north side exhibited more consistent trends. The greater variability in south-side temperatures was believed to be caused by the shading effect from adjacent trees as noted previously by Powell (1967) and in our prior discussion.

Maximum north-side temperatures rarely exceeded 90°F in any of the plots. In contrast, south-side temperatures exceeded 100°F on at least one tree in each GSL. The maximum south-side temperature observed was 113°F in the Brownsville GSL 60 plot, and it was not unusual for south-side temperatures to exceed 100°F several times during midday.

In 1967, Powell indicated that maximum surface bark temperatures in this lodgepole pine stands were 70 and 91°F for north and south sides, respectively. His temperatures seem most closely related to the north and south temperatures on our GSL 80 trees (see Fig. 5 for general bark temperature trends on a clear day). Although Powell does not state the stocking level of his stand, we assume the MPB infested a stand near 150 GSL. If so, then Powell's maximum temperatures are considerably higher than our GSL 150 temperatures and may reflect differences in crown and canopy characteristics of lodgepole versus ponderosa pine.

Temperature differences, GSL, and MPB infestations

The general relationship between bark temperatures and GSLs is that in GSLs < 80, trees were warmer than in

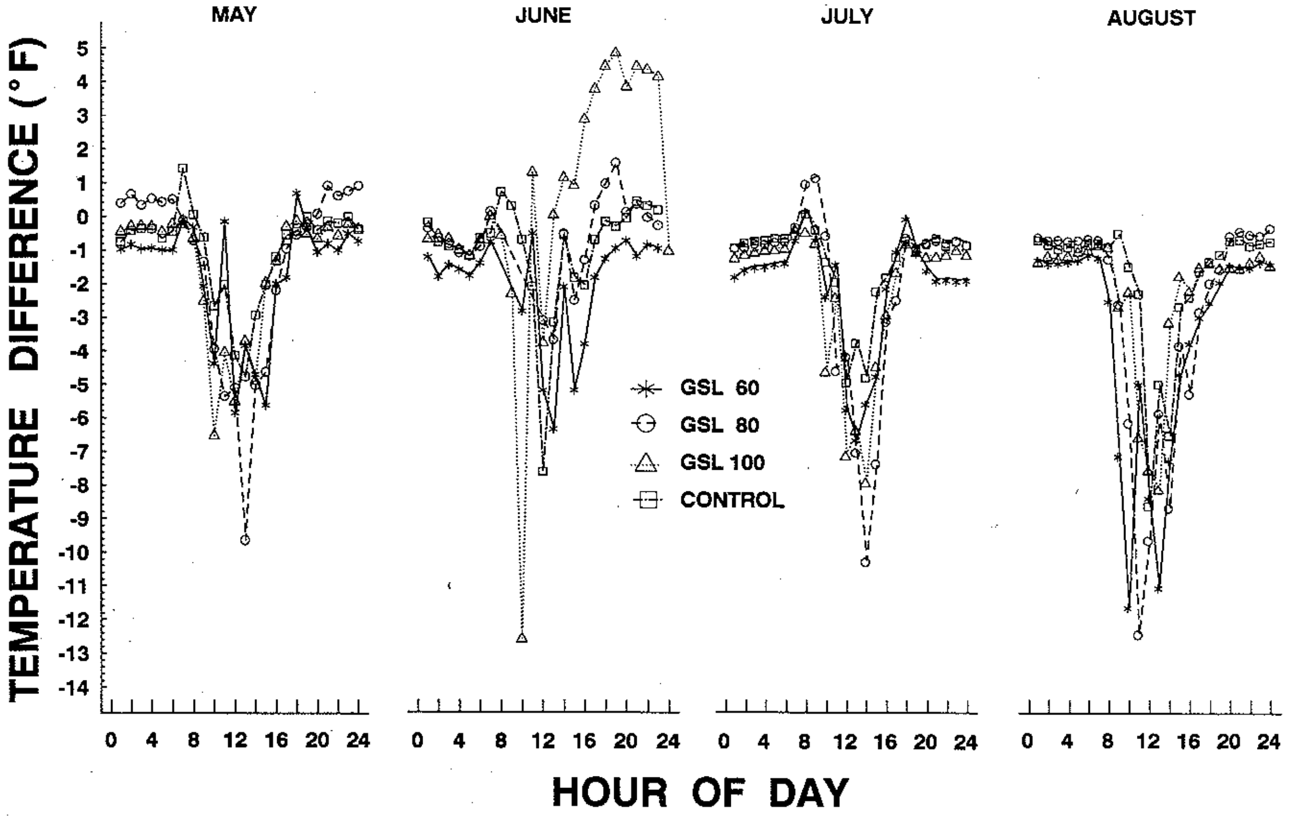

FIG. 4. Mean differences between north and south bark temperatures (°F) for each growing stock level (GSL) at Brownsville by month and hour of the day. Temperature difference is the north-side temperature minus the south-side temperature. Negative temperatures indicate that south sides are warmer.

GSLs > 150 (control) during diurnal periods on clear days. GSL 100 trees were intermediate in temperature to those of GSL < 80 and GSL > 150 and rarely statistically warmer than GSL 150 trees. Presumably, bark temperatures in GSLs between 100 and 150 would be very similar to temperatures of the GSL 150 trees. From a statistical viewpoint, GSL 100 stands may be the lowest stocking level where the stand temperatures conducive for attack are first consistently found.

Although mean temperatures may not have been statistically different, biologically the differences may be important. MPB commonly infest stands similar to our control plots (ca. GSL 150), whereas stands of GSL 80 in the Black Hills have been relatively unsusceptible to MPB attack in the past 15 years. Temperature differences between these two stocking levels during midday in July and August, the MPB attack period, were more than 5°F in the Experimental Forest plots (Fig. 1) and 4 to 5°F in the Brownsville plots (Fig. 2). However, to rely heavily on mean temperatures may be misleading because they represent a combination of temperatures from cloudy overcast days as well as mostly sunny days.

Temperature patterns on cloudy days were similar to those of clear days but with less variability and smaller differences among the means. Bark temperatures in the lower GSLs were 3 to 5°F warmer than the controls during midday, and only 1 to 2°F different at other hours. During hours when maximum differences were developing, mean bark temperatures on cloudy days in July and August rarely exceeded 75°F. Although bark temperatures with these differences among GSLs may be statistically significant, biologically all GSLs would be equally susceptible on cloudy days because bark temperatures of this magnitude would not deter MPB selection of any stand. In contrast, bark temperatures on mostly sunny days differed between the lower GSLs and the controls by more than 10°F, and south-side temperatures on trees in the lower GSLs exceeded 90°F.

The critical role of bark temperatures may well depend on the weather conditions existing during the attack period. Cloudy or overcast skies depress temperature differences between GSLs and, therefore, make all GSLs equally susceptible from the bark temperature standpoint. However, overcast skies with light precipitation or thundershowers shut down MPB emergence because the emergence temperature threshold is not reached (J.M. Schmid, personal observation). The importance of the mostly cloudy condition is thus negated. In contrast, sunny to partly cloudy days are more conducive for MPB emergence and therefore suggest an important role for bark temperatures.

Bark temperatures and MPB behavior

Temperature influences MPB behavior and development (Safranyik 1978). Although our study did not examine MPB behavior in relation to temperature, bark temperatures could explain several aspects of MPB behavior. First, beetles emerge when air temperatures reach about 59°F (McCambridge 1974) and no emergence occurs below 55°F (Schmid 1972). Based on the bark temperature data for July and August from both locations, and using a threshold temperature of 59°F, day to day emergence of the MPB could be predicted. In late July, temperatures were above 60°F throughout some 24-h periods and therefore conducive for MPB emergence the entire day. On days in August, the

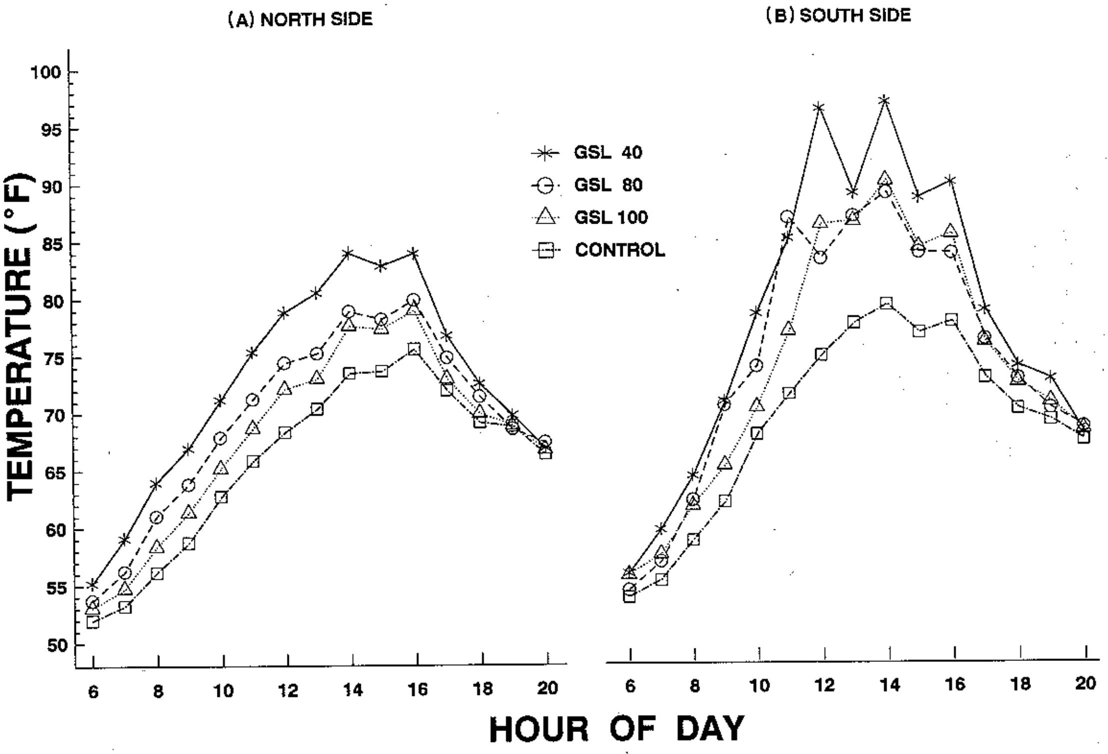

FIG. 5. Mean bark temperature (°F) for (A) the north and (B) the south sides of trees in four growing stock levels (GSL) on the Experimental Forest for a clear day in August.

emergence pattern would have varied by GSL. Emergence may have begun in the Experimental Forest plots as early as 07:00 in the GSL 40 stand (Fig. 5) and not until 09:00 in the control (GSL > 150). At the Brownsville site, emergence would have begun between 09:00–11:00 because threshold temperatures were not attained until then.

Second, temperature patterns may partially explain diurnal MPB attack behavior. MPB attacks over a 24-h period show a distinct pattern of reduced frequency during midday (Edson 1978) and increased frequency around 18:00 (Edson 1978; McCambridge 1967). The decreased number of attacks during midday coincides with the period of highest mean temperatures in all GSLs and periods when south-side temperatures in GSL < 80 plots may commonly exceed 90°F.

The increased frequency of attacks around 18:00 coincides with a period when bark temperatures were declining but still well above the emergence temperature threshold (air temperature = 59°F). After 15:00, temperatures on the hottest days were <80°F in all GSLs trees except the GSL 40 plot. The increased frequency of attacks after 16:00 (McCambridge 1967) and at 18:00 (Edson 1978) suggests that MPB may prefer temperatures of 65–80°F for attacking. In this temperature range, most GSLs would be susceptible to attack from a temperature standpoint before midday and after 15:00. Stands with GSL > 150 (control) may be preferred by MPB because temperatures seldom exceed 80°F even during midday.

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