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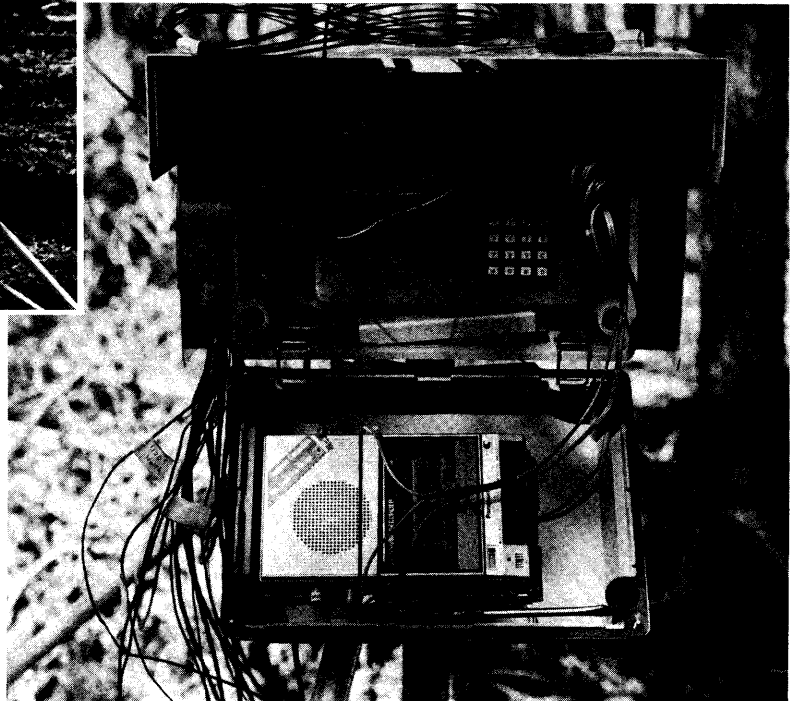
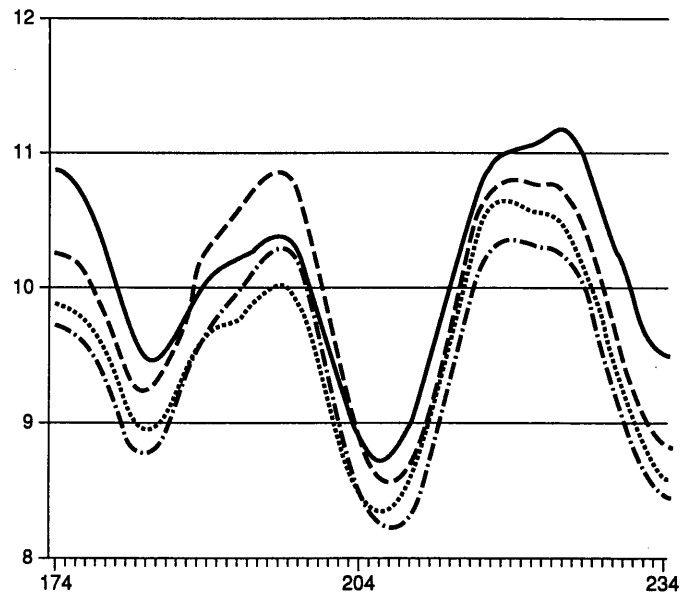
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Effects of Thinning on Temperature Dynamics and Mountain Pine Beetle Activity in a Lodgepole Pine Stand

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Research Summary

Temperature measurements were made to better understand the role of microclimate on mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae), activity as a result of thinning lodgepole pine stands. The study area is on the north slope of the Unita Mountain Range in northeastern Utah. Sampling was done over 61 days starting June 23, 1987 (174). Eight lodgepole pines, *Pinus contorta* var. *latifolia* Engelm., were sampled for surface and subsurface (phloem) temperatures in a thinned and unthinned stand. Principal components analysis was applied to all temperature variables. Most of the variation was attributed to two variables, coolest part of the night (1:00 a.m. to 9:00 a.m.) and hottest part of the day (1:00 p.m. to 6:00 p.m.). These two variables were smoothed using time series analysis that permitted us to see general patterns and small differences between tree temperatures. The thinned stand was approximately 1 °C warmer than the unthinned stand and the day temperature was 10 to 11 °C higher than the corresponding night temperature. Models were developed to predict phloem temperature from bark surface temperature. The resultant equations had r^2 values of 0.98 or greater.

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Introduction

Thinning has been used in the past to increase tree vigor (Graham and Knight 1965; Keen 1958), and tree resistance to attacks by mountain pine beetle. The removal of large-diameter lodgepole pines, which are preferred by mountain pine beetle, can also result in a reduction in tree loss during beetle epidemics (Cahill 1978; Cole and others 1983; Hamel 1978; McGregor and others 1987). Reduced tree losses occur before residual trees can express resistance by increased growth (Amman and others 1988). This phenomenon suggests that factors other than vigor may be responsible for reductions in mountain pine beetle infestations.

Thinning forests can cause subtle changes in tree physiology (Nebeker and Hodges 1983) and microclimate, especially temperature (Bartos and Amman 1989; Schmid and others 1992). In western North America, changes brought about by thinning lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) forests have had profound effects on mountain pine beetle (*Dendroctonus ponderosae* Hopkins [Coleoptera: Scolytidae]) behavior (Schmitz and others 1989), resulting in reduced tree mortality in thinned stands (McGregor and others 1987).

In addition to increasing growing space, thinning also affects parameters of the physical environment, such as temperature, light, and wind speed. Temperature is an important factor in the ecology of insects as it affects the physical conditions of habitat and the physiology of insects themselves (Safranyik 1978; Wellington 1950). In the case of mountain pine beetle, observations were made on the effects of extremely high (Patterson 1930) and low (Somme 1964; Yuill 1941) temperatures. Between the extremes is an optimum zone of temperature that may be modified by other microclimatic factors (Rudinsky 1962).

We explored the effects of temperature on altered lodgepole pine stands because (1) temperature changes are immediate following tree removal from

the stand, and (2) growth of residual trees is usually slow to respond to thinning. The objective of this study was to determine the surface and subsurface bark temperature variability between thinned and unthinned lodgepole pine forest and to relate these differences to mountain pine beetle activity.

Methods and Materials

The study site is south of Mountain View, WY, on the north slope of the Uinta Mountains in north-eastern Utah. Mature lodgepole pine (80-120 years old) occupy the site, which is on the Wasatch-Cache National Forest at an elevation of 2,865 m. Part of the site was thinned in the early 1970's. Replicating the thinning treatment was not possible because of the length of time since treatment and the prohibitive cost of equipment to monitor numerous sites. We decided that useful information could still be obtained by selecting adjacent stands (thinned and unthinned). These two stands were selected so that physical characteristics, such as slope, aspect, and elevation were uniform.

The stands were sampled for 61 days during the summer of 1987 to determine bole's surface and subsurface (phloem) temperature. During 1986 the area had a very active mountain pine beetle infestation and was used for an in-depth study of numerous microclimatic differences including; temperature, incident solar radiation, windspeed, wind direction, and stand temperatures (Bartos and Amman 1989). Beetles were captured during peak flight time in both thinned and unthinned stands in 1986; only 5 percent of the total beetles caught were in the thinned stand. The epidemic beetle population was not active during the summer of 1987.

Stand Characteristics

Characteristics of the thinned and unthinned lodgepole pine stands were determined through variable plot (10 BAF) cruising. Plots were placed

50 m apart in a grid pattern in each stand. Lodgepole pine trees on each plot were tallied as to live or dead by cause of death and were measured for diameter at breast height (d.b.h.). The dominant or co-dominant tree closest to plot center was measured for height and crown length. Stand density was expressed in terms of basal area and number of trees per hectare.

Monitoring Temperature

An automatic recording device (21X micrologger, Campbell Scientific) was used to measure the temperatures for a 61-day period starting June 23, 1987 (174). This time period encompassed the "peak" mountain pine beetle flight period, which usually occurs in this area the last week in July and the first week in August (Bartos and Amman 1989). The time prior to flight was included to monitor the temperature that existed during the final stages of beetle maturation. Eight trees were monitored in each of the two treatments. Initially, the instrument tower site was randomly selected within each stand. The eight sample trees were located around this tower and the distance from the tower to each sample tree was limited by the temperature sensor "leads." All sample trees were similar in height, crown length, and d.b.h. (approximately 22 cm).

Temperature sensors were connected to the micrologger to measure temperature at two points on each sample tree. These temperature sensors were placed at breast height (b.h.) 1.3 m aboveground, on the bark surface, and immediately below the surface, on the south side of the trees. Temperatures measured in these stands in 1986 (Bartos 1988) showed that a strong relationship existed between the surface temperature on the north and south side of the tree. Therefore, only the south side was measured to maximize the number of sample trees.

The below-outer bark surface sensor was positioned in the phloem because phloem is the substratum in which mountain pine beetle adults mine and lay eggs and the developing larvae use it as food. This sensor was placed just below the thin bark of the tree and was gently forced a couple of mm into the phloem.

Data Analysis

Characteristics (density, basal area, d.b.h., tree height, and crown length) of thinned and unthinned stands obtained during stand surveys were subjected to analysis of variance to test for significant differences between treatments (Bartos and Amman 1989).

Our basic daily data consisted of eight values, each being the mean of three hourly measurements.

These means were labeled: 1:00 a.m., 4:00 a.m., 7:00 a.m., 10:00 a.m., 1:00 p.m., 4:00 p.m., 7:00 p.m., and 10:00 p.m. The mean labeled 1:00 a.m. was the average of three temperature measurements taken at 1:00 a.m., 2:00 a.m., and 3:00 a.m. Other means are defined similarly. The measurements were taken each day for 61 days.

A further reduction in the number of variables that needed to be dealt with was attempted by using a modification of principal component analysis, somewhat similar to that used by Jassby and Powell (1990). The objective was to identify fewer than eight daily means that would capture all the essential information on daily temperature patterns. Such variables would also have the additional property of being independent and thus capable of being studied one at a time.

The principal components analysis indicated that only the first two principal components accounted for virtually all the variability within a given day. Further, the first principal component was essentially the mean of the mean temperatures labeled 1:00 a.m., 4:00 a.m., and 7:00 a.m. We chose to use a simple unweighted mean of these three temperatures and refer to it as the nighttime mean temperature. Likewise, the second principal component was essentially the mean of the mean temperatures at 1:00 p.m. and 4:00 p.m. Again, we chose to use the simple mean of these two temperatures to represent the second principal component and refer to it as the daytime mean temperature. Because of the close relationships between these two variables and the first two principal components, the two variables are very nearly independent at any given time. Of course, they are not serially independent over time (Booth 1993).

The nighttime and daytime mean temperatures were analyzed as time series. We knew in advance that there was variability from one measurement to the next during the course of the 61-day study. To study the underlying temperature patterns, we applied the Daniell (1946) window, a smoothing process, to each of the time series.

The application of this smoothing method eliminated all high frequency oscillations. Residuals from these smoothed values had all major, low-frequency patterns removed, and a fourier analysis of them produced no detectable periodicities in the data. Therefore, graphs of the smoothed values themselves can be expected to convey all pertinent information relating to temperature patterns in the data.

Schmid and others (1992) found a strong correlation between bark temperature and ambient air temperature. If possible, we were interested in establishing a relationship between bark temperature

and phloem temperature. Therefore, we performed model fitting on 61 nighttime means and on 61 daytime means. We further divided the data into those obtained on the thinned stand and those obtained on the unthinned stand. Thus, we obtained a total of four fitted models: both a nighttime and daytime model for the thinned stand and two analogous models for the unthinned stand. The models were fit using data from five trees in the unthinned stand and from four trees in the thinned stand. These trees were selected because the remainder of the eight trees produced incomplete data sets.

Results

We looked at the results in terms of both stand characteristics and temperature.

Stand Characteristics

The thinned stand had an average basal area of 22.1 m²/ha, a density of 708 trees/ha, and an average d.b.h. of 20.2 cm. Dominant and codominant trees averaged 15.1 m in height, with live crown being 52 percent of total height. The adjacent unthinned stand had a basal area of 37.0 m²/ha, a density of 1,090 trees/ha, and an average d.b.h. of 18.6 cm. Dominant and codominant trees averaged

15.1 m high, with live crown being 53 percent of total height (Bartos and Amman 1989). Of these stand characteristics, only the basal area and trees per hectare were significantly different between stands ($P < 0.05$) at this point in time—approximately 20 years after thinning. When the stands were monitored, the effects of the treatment were still pronounced.

Temperature

The three main questions of interest regarding temperature dynamics are: (1) "What is the difference in temperature pattern between the thinned and the unthinned stands?", (2) "What is the difference in pattern between the air temperature and the phloem temperature?", and (3) "What is the difference in pattern between the temperatures at the warmest time of the day and those at the coolest part of the night?" Data relating to these questions appear in figures 1 to 3, respectively.

To facilitate answering these three questions, the data were broken into four groups: measurements taken in the air in the thinned stand (AT), in the phloem in the thinned stand (PT), in the air in the unthinned stand (AU), and in the phloem in the unthinned stand (PU). The measurements in AT and PT are from the same trees in the thinned

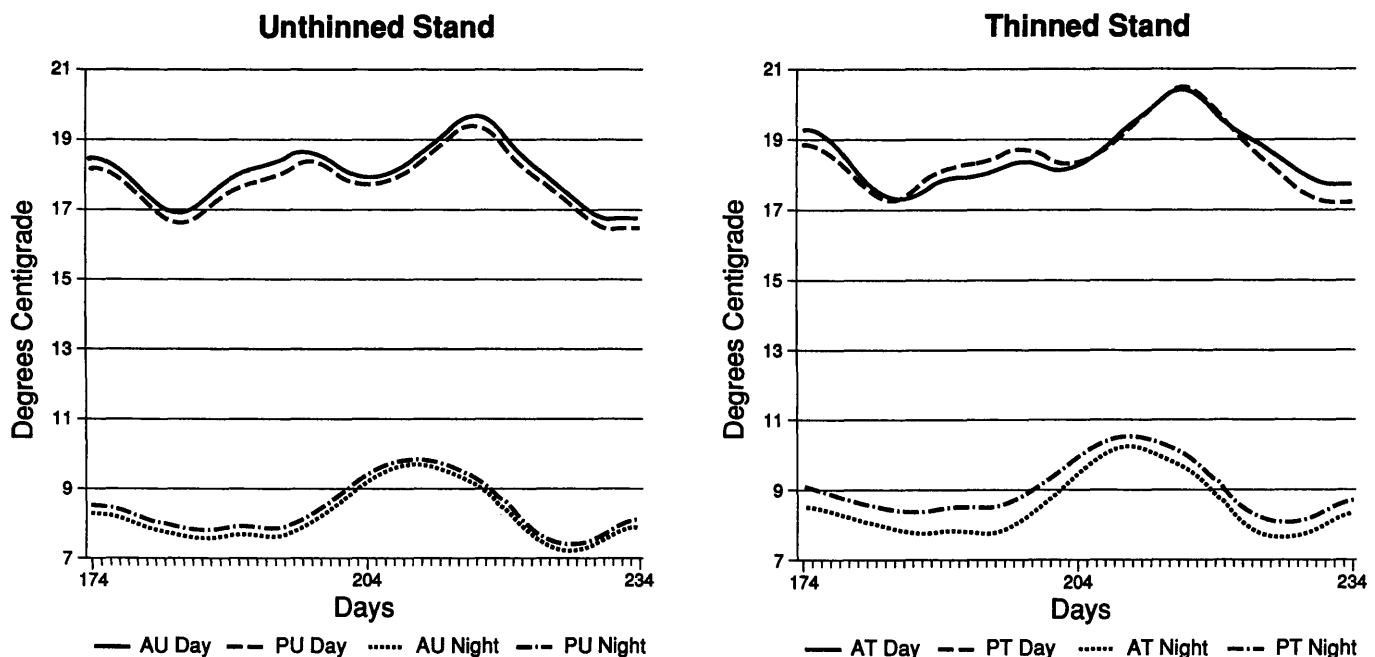


Figure 1—Smoothed curves showing treatment differences for 61-day time period between June 23 and August 22, 1987. Sets of curves represent the hottest and coldest part of the day. First letter of the code refers to position of temperature probe (A = air = phloem) and second letter refers to treatment (T = thinned and U = unthinned).

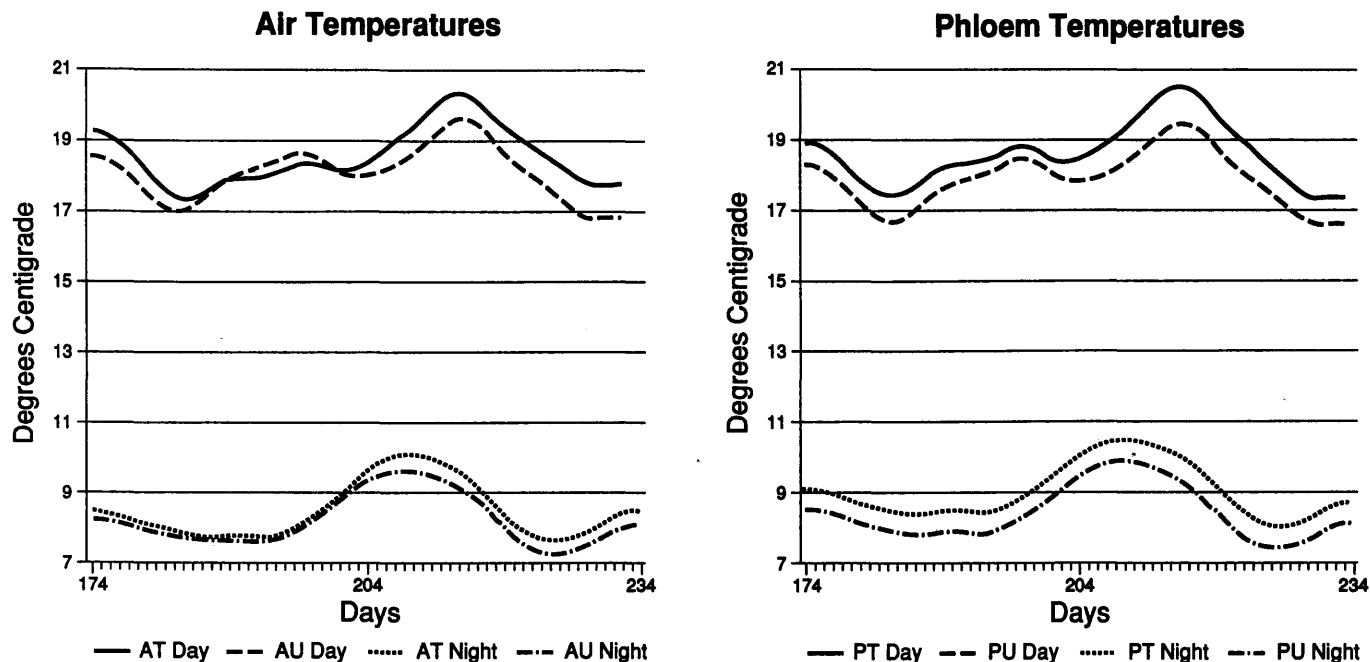


Figure 2—Smoothed curves showing temperature differences for 61-day time period between June 23 and August 22, 1987. Sets of curves represent the hottest and coldest part of the day. First letter of the code refers to position of temperature probe (A = air and P = phloem) and second letter refers to treatment (T = thinned and U = unthinned).

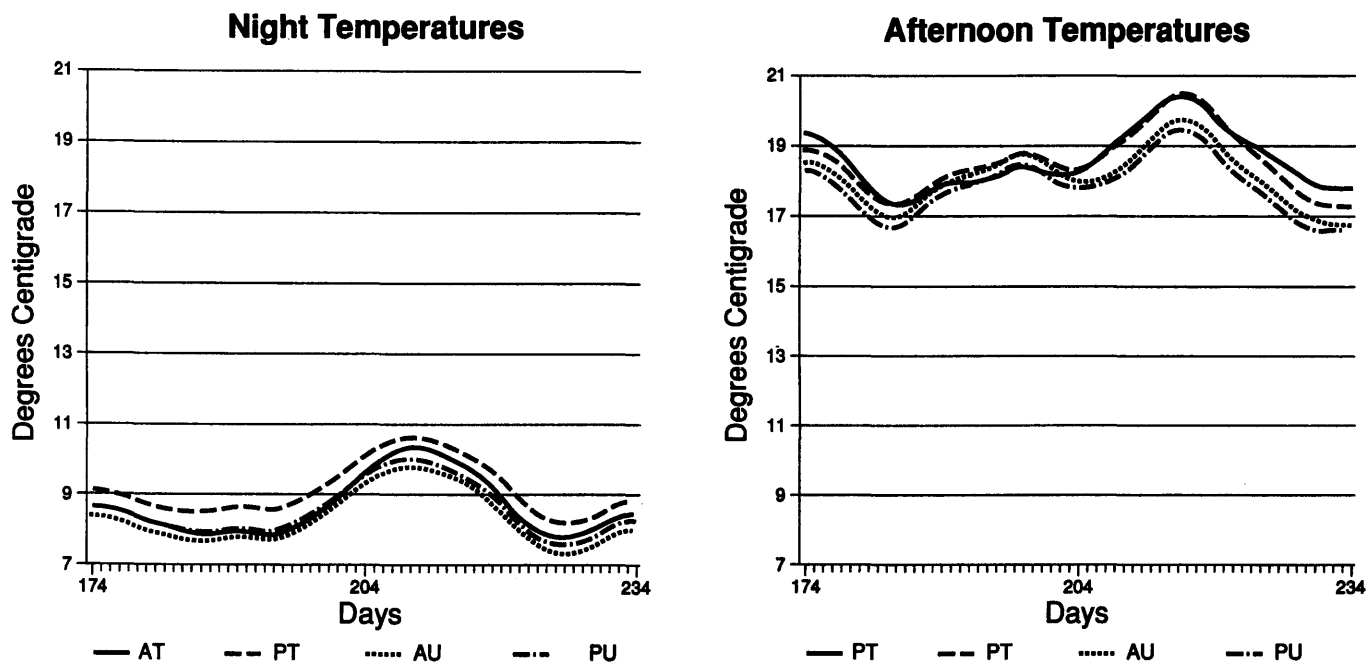


Figure 3—Smoothed curves showing temperature differences of the hottest and coldest part of the day for a 61-day time period between June 23 and August 22, 1987. First letter of the code refers to position of temperature probe (A = air and P = phloem) and second letter refers to treatment (T = thinned and U = unthinned).

stand and, thus, are paired. Likewise those in AU and PU are from the same trees in the unthinned stand and are paired. These groupings are maintained throughout the analyses and resulting graphs.

A fourth question of interest regards the temperature increase from the coolest part of the night to the warmest part of the afternoon. These increases are presented in figure 4.

Two variables (principal components) accounted for high percentages of the variability in temperature from day to day (see table 1). Therefore, only these two variables were studied. The first is the warmest part of the afternoon (1:00 p.m. to 6:00 p.m.), which is referred to as the "day" variable, and the second is the coolest part of the night (1:00 a.m. to 9:00 a.m.), which is the "night" variable. The high percentages shown in table 1 indicate that if the actual principal component had been used, complete independence would have resulted. However, this would have required using a different weighted mean for each of the four data groups. Because the weights (coefficients from the principal components analysis) were quite similar for the hours specified in "day" and also in "night," unweighted means for the appropriate hours were used in all analyses. This makes the variables from the four data groups

Table 1—Percentages of total day-to-day variability explained by eigenvalues in principal component analysis.

Data group	Percent of day-to-day variability		
	Night	Day	Cumulative
AT (thinned stand on surface)	66	25	91
PT (thinned stand in phloem)	68	25	93
AU (unthinned stand on surface)	69	24	93
PU (unthinned stand in phloem)	69	24	93

comparable. Figures 1 to 4 contain the smoothed values of the day and night means.

A final point of interest was the development of models to predict phloem temperature from bark surface temperature. The estimates of variance for the fitted models were based on means of several trees. Because we wished to predict phloem temperature for an individual tree and because the variance is larger for an individual tree than for a mean of several trees, we inflated these variances to reflect proper prediction intervals on an individual tree basis. These intervals are presented in figure 5. The resulting models (table 2) show there is a strong correlation ($r^2 \geq 0.98$) between bark surface and phloem temperatures.

Thinned vs. Unthinned—Temperature curves for the 61-day period were very similar between the thinned and unthinned stands (fig. 1). Similar patterns were obtained for both the hottest and coldest part of the day for both the thinned and unthinned stands. Subsurface (phloem) temperatures were similar to those on the bark surface (air).

In the unthinned stand the air temperature was higher than the phloem temperature during the day with a reversal occurring at night.

In the thinned stand, the same general condition held with the exceptions that for most of the month of July the phloem temperature during the day was warmer than the air temperature. This phenomenon probably can be attributed, in part, to overcast skies during this period. The thinned stand was more open; therefore, atmospheric conditions could have a more subtle effect on the temperatures, such as increase in radiant warming. Another condition in the thinned stand was the larger difference

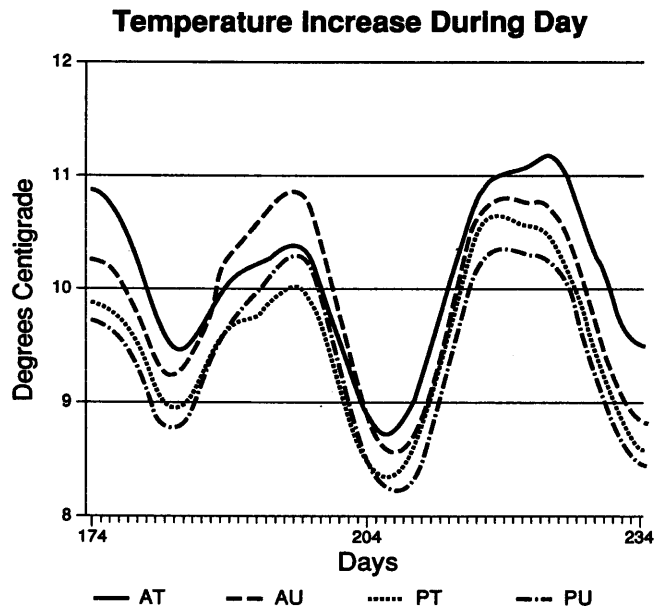


Figure 4—Smoothed curves showing temperature increases from the coldest to the hottest part of the day for a 61-day time period between June 23 and August 22, 1987. First letter of the code refers to position of temperature probe (A = air and P = phloem) and second letter refers to treatment (T = thinned and U = unthinned).

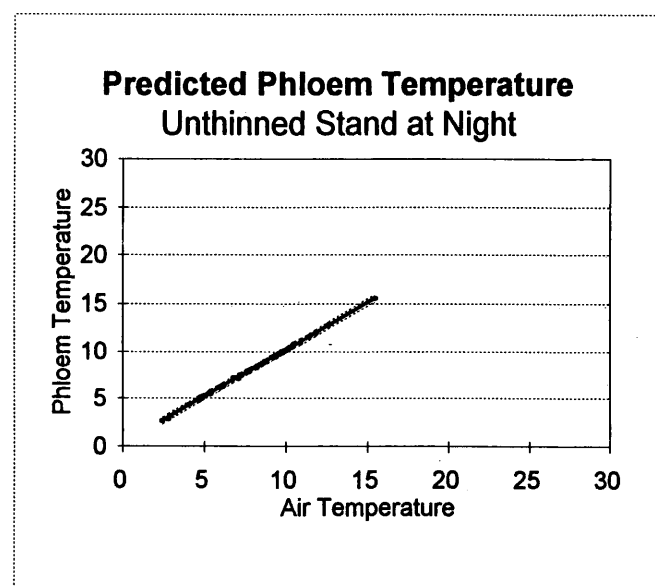
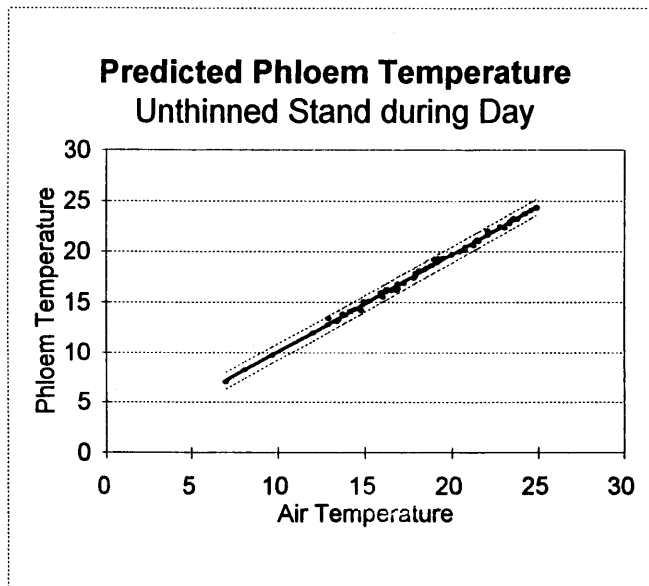
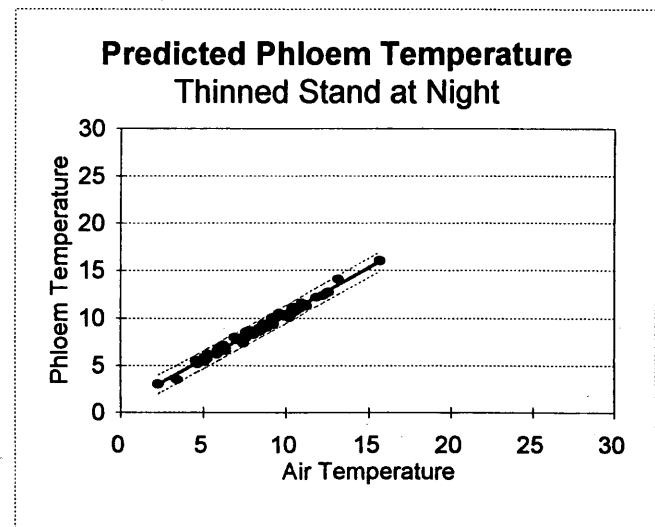
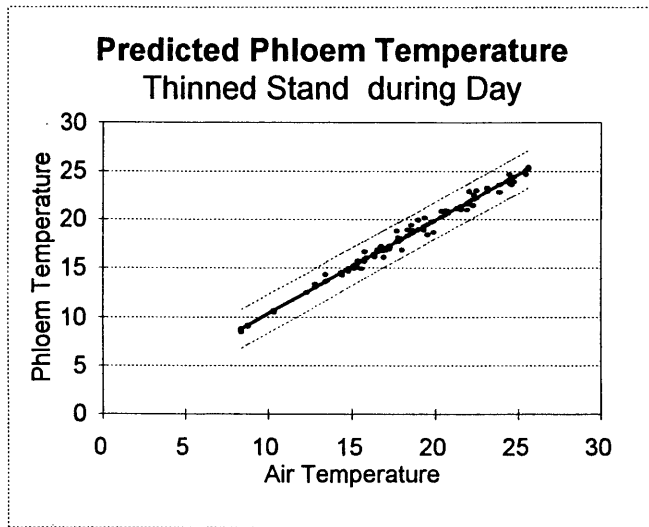


Figure 5—Plots of variance associated with models developed to predict phloem temperature from bark surface temperature. Treatment/time represented are (A) thinned/daytime, (B) unthinned/daytime, (C) thinned/nighttime, and (D) unthinned/nighttime.

Table 2—Equations that predict phloem temperature from bark surface temperature for four treatment/time situations.

Treatment	Predictive equation	R^2
Thinned night	$\hat{y} = 0.81324 + 0.96285 \cdot \text{BarkSur}$	0.9871
Thinned day	$\hat{y} = 0.81383 + 0.95340 \cdot \text{BarkSur}$	0.9798
Unthinned night	$\hat{y} = 0.28213 + 0.90000 \cdot \text{BarkSur}$	0.9986
Unthinned day	$\hat{y} = 0.4105 + 0.96250 \cdot \text{BarkSur}$	0.9973

between phloem and air temperatures at night. This was due to a consistently higher night-time phloem temperature in the thinned stand. Overall, the measured temperature in the thinned stands was warmer by about 1 °C. This difference does not appear large; however, if accumulated over a period of time it could have an effect on beetle development.

Air vs. Phloem—Graphs of temperature in the air displayed similar patterns in both day and night measurements (fig. 2). The curves for night temperature contain smoother and less volatile patterns. Nevertheless, the same general patterns prevail in both sets of measurements. While the night

temperature was consistently higher in the thinned stand, the day temperature crossed over for most of the month of July. During this period, the unthinned stand had a higher temperature than the thinned stand. This was probably due to an extended period of cloud cover. Day temperatures were approximately 10 to 11 °C higher than the corresponding night measurements.

Night vs. Day—While day temperatures varied between 16 and 20 °C (fig. 3, right), the corresponding night temperatures varied between 8 and 10 °C (fig. 3, left). Again, the curves for night temperature demonstrate less fluctuation than did their day temperature counterparts. There was a consistency in the night temperatures for all four groups (fig. 3, left). The exception was the night phloem temperature in the thinned stand. It was consistently about 0.5 °C higher than the temperature of the other three groups. Over the 61-day length of the study, this would produce an additional 30 degree-day heat buildup in the phloem. This change is probably sufficient to advance beetle development in the thinned stand.

Daily Temperature Differentials—Daily temperature differentials were plotted (fig. 4) as the difference between the daytime and the nighttime temperatures for each of the 61 days of the study. These plotted differentials contain three distinct peaks. The graphs of temperature in the phloem for both day and night were consistently higher in the thinned stand than in the unthinned stand (fig. 4). Differences between the curves were between 0.5 and 1.0 °C. The nighttime temperatures displayed less pronounced overall fluctuation than did the daytime temperatures. However, both follow the same general patterns. The daily temperature differential averaged about 9.75 °C and ranged between 8 and 11 °C. The daily temperature increase was roughly 0.5 °C more in the air than in the phloem. In both the air and in the phloem, temperatures in the thinned stand increased more than in the unthinned stand, except during the period for most of the month of July. Again, this crossover was probably due to prolonged cloud cover.

Discussion

Tree density is probably one of the biggest contributors to microclimate differences observed in these lodgepole pine stands. The main difference between the thinned and unthinned stands was density of live trees (Bartos and Amman 1989). There was less basal area (15 m²/ha) and fewer trees (292/ha) in the thinned stand than the unthinned one. Diameter at breast height (d.b.h.)

was not significantly different between the thinned and unthinned stands; the two treatments had an average of 20 and 18 cm, respectively. These similar diameters would indicate there was no rapid release in growth of these trees as a result of thinning. These d.b.h. averages were just slightly smaller than the average of 22 cm d.b.h. obtained from the sample trees.

Thinning lodgepole pine stands resulted in increased light intensity, wind movement, insolation, and temperature (Bartos and Amman 1989). Our study verifies that trees in thinned lodgepole pine stands generally have higher phloem and bark surface temperatures than trees in unthinned stands. Schmid and others (1992) found phloem and bark surface temperatures to be higher in thinned lodgepole pine stands than in unthinned stands for daylight hours.

As a result of our regression development between bark surface and phloem temperature, we found the variation to fluctuate within the treatment/time scenarios. Most of the variation was associated with the thinned/day situation and the least variation occurred in the unthinned/night situation. These observations further support the thesis that thinning lodgepole pine stands disrupts temperature patterns and corroborate the work of Schmid and others (1992).

It has been speculated that temperature can affect mountain pine beetle activity. We observed that microclimate differences between thinned and unthinned lodgepole pine stands were sometimes quite subtle. However, even minor changes in microclimate, especially temperature, can have profound effects on mountain pine beetle development (Bentz and others 1991) and probably behavior (Schmitz and others 1989).

Subsurface temperatures never exceeded 21 °C (day) or 11 °C (night) for our 61-day sample period. This is considerably less than the occasional 35 °C temperature Powell (1967) reported for subcortical regions on the south sides of lodgepole pine trees.

Cooler surface temperatures of trees apparently provide a more attractive physical environment for mountain pine beetles. Thus, attack densities of mountain pine beetle are higher on cooler surfaces (north side) of trees (Reid 1963; Shepherd 1965). To further substantiate this, Mitchell and others (1983) found strip attacks to occur primarily on the north and east sides of trees.

The effect of temperature on mountain pine beetle behavior may be more than a direct inhospitable physical environment—hot bark. Mountain pine beetle may have evolved behavior strategies that allow them to survive by avoiding situations not favorable to their development. For example, in

thinned stands, where phloem temperatures are a few degrees above those in unthinned stands, mountain pine beetle may proceed too far in their development and not be able to overwinter as successfully. It has been shown that mountain pine beetles entering winter in the pupal and teneral adult stages are more susceptible to freezing than larvae (Amman 1973; Reid 1963).

Conclusions

Temperature is an important variable of lodgepole pine stands that may play a vital role in mountain pine beetle behavior. The summer of 1987 appears to have been cooler than normal on this north slope Uinta study site. This could have contributed, in part, to the collapse of the beetle epidemic in this area.

Principal component analysis indicated that virtually all temperature variation during a single day could be summarized in just two measurements: the average temperature during the coolest part of the night and the average temperature during the warmest part of the afternoon. Furthermore, these two measurements can be studied independently. Smoothing these two variables permitted us to see patterns and even small differences between tree temperatures in (1) thinned compared with unthinned stands, (2) the phloem compared with the surface of the tree, and (3) the coolest part of the night compared with the hottest part of the day.

A strong relationship was found to exist between bark surface and phloem temperature. Variation associated with the resultant equations increased with thinning and daytime versus nighttime attributes.

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Temperature measurements were made to better understand the role of microclimate on mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae), activity as a result of thinning lodgepole pine stands. Sampling was done over 61 days on the north slope of the Unita Mountain Range in northeastern Utah. Principal components analysis was applied to all temperature variables. Most of the variation was attributed to two variables, coolest part of the night and hottest part of the day. The thinned stand was approximately 1 °C warmer than the unthinned stand. Day temperature was 10 to 11 °C higher than the corresponding night temperature. Models were developed to predict phloem temperature from bark surface temperature. The resultant equations had r^2 values of 0.98 or greater.

Keywords: time series, principal components, smoothing, *Dendroctonus ponderosae*, *Pinus contorta*



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