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Solar Treatments for Reducing Survival of Mountain Pine Beetle in Infested Ponderosa and Lodgepole Pine Logs

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Abstract

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Three experiments were conducted to evaluate the use of solar radiation for reducing survival of mountain pine beetle populations in infested logs. Ponderosa pine logs were used in experiments 1 and 2 and lodgepole pine logs were used in experiment 3. Experiment 1 comprised three treatments: (1) one-layer solar treatment without plastic sheeting and logs rotated one-third of a turn once a week; (2) two-layer solar treatment with plastic sheeting; and (3) two-layer solar treatment without plastic sheeting. For experiment 2, two additional one-layer treatments were added: one-layer treatment with plastic sheeting and no rotation and a one-layer with no plastic sheeting and no rotation. Experiment 3 included all the above-mentioned one-layer treatments only. For all experiments, brood density per 0.05 m^2 (0.5 ft^2) was estimated before and after treatment and analyzed using repeated measures analysis of variance. Subcortical temperatures were monitored in one replicate of all treatments in all experiments. In experiment 2, phloem moisture was monitored before and after treatment in uninfested logs. All treatments in all experiments caused drastic reductions in brood survival. In experiment 1, the one-layer treatment with the logs rotated once a week significantly reduced brood survival compared to the two-layer without plastic sheeting treatment but was not different from the two-layer with plastic sheeting treatment. There were no differences in brood survival after treatment associated with any treatments in experiments 2 and 3. In all experiments brood survival was consistently reduced in the aspects of the logs exposed to the sun. Maximum temperatures were consistently higher in the treatments with plastic sheeting, the exposed surfaces of the logs to the sun, and the upper layer of logs in the two-layer treatments. No differences were detected in phloem moisture content in uninfested logs before and after treatment in experiment 2, suggesting that heat is directly responsible for the observed reductions in survival. We conclude that solar treatments are an effective alternative for reducing mountain pine beetle survival in infested ponderosa and lodgepole pine logs.

Keywords: mountain pine beetle, *Dendroctonus ponderosae*, solar treatments, mountain pine beetle control

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Introduction

Periodic outbreaks of mountain pine beetle (*Dendroctonus ponderosae*) cause significant mortality of ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*Pinus contorta*) in Colorado and other parts of the Western United States. With increased incidence of infested trees, Federal, State, and private land managers face the predicament of what to do with these trees to prevent or reduce further infestations. This situation is particularly important in high-value areas such as campgrounds or near private homes. Under certain circumstances, managers and landowners can salvage previously killed and currently infested trees. There are no chemicals available for killing mountain pine beetles in infested trees. Preventive insecticide applications can be used to protect high value trees from attack. Nonetheless, chemicals available for this use are limited, and many landowners are reluctant to use insecticides because of environmental concerns.

The use of solar heat or radiation has been considered as an option for many decades (Craighead 1920; Graham 1924; Massey and Wygant 1954; Patterson 1930). Various studies have examined the use of solar treatments for control of bark beetles in infested logs. Results from the different studies exhibit variations in efficacy, depending on the methodology utilized and the tree species examined. *Ips*-infested ponderosa pine has been successfully treated in Arizona using 4-mil clear plastic sheeting (Buffam and Lucht 1968). Average beetle mortality in slash piles covered with clear plastic sheeting was 89 percent, compared to 11 percent for black plastic sheeting-covered piles and 5 percent for uncovered piles. Average high temperature recorded under the piles was highest with the clear plastic at 74.4 °C (165.9 °F). Mitchell and Schmid (1973) tested solar treatments in Engelmann spruce (*Picea engelmannii*) for control of spruce beetle (*Dendroctonus rufipennis*). That study found 90 percent or greater mortality in the top surface of logs but no significant mortality on the sides of the logs. This suggests that direct exposure is important in subsequent mortality in uncovered logs. McCambridge and others (1975) used fumigation treatments with the insecticide ethylene dibromide in combination with clear 6-mil plastic sheeting to kill mountain pine beetles in ponderosa pine that was to be used for firewood in Colorado. Population reduction was complete in insecticide-treated piles. In stacks covered with plastic but not treated with insecticides, population reduction was small on average but relatively high in the top of the stack, suggesting that solar radiation contributed to beetle mortality by increasing temperature to lethal levels. Holsten and Werner (1993) working with spruce beetle (*Dendroctonus rufipennis*)- infested Lutz spruce (*Picea* x *lutzii*) in Alaska indicated that neither clear nor black plastic sheeting was effective for attaining significant mortality of that species. Higher bark surface temperatures were obtained with clear plastic sheeting when compared to black plastic sheeting or uncovered stacks of infested material. Inner bark temperature, however, was higher in uncovered stacks. Some mortality was observed, but temperatures did not reach levels sufficiently high to cause extensive mortality (Holsten and Werner 1993).

Increasing populations of mountain pine beetle in Colorado have sparked new interest in strategies to treat infested logs in high-value areas. In the past, practitioners and landowners in Colorado have used different forms of solar radiation treatments for mountain pine beetle. However, quantitative data to support recommendations are lacking.

In this study, we examine the use of solar treatments for reducing survival of mountain pine beetle in infested ponderosa and lodgepole pine logs in Colorado.

Methods

Study Sites and Experiments

Three experiments were conducted. Experiments 1 and 2 were conducted in ponderosa pine during June and July 1999 and May through July 2000, respectively, on the Canyon Lakes Ranger District of the Arapaho-Roosevelt National Forest, Colorado. Experiment 3 was conducted in lodgepole pine during June and July 2000 on the Sulphur Ranger District of the Arapaho-Roosevelt National Forest (table 1).

Experiment 1—This experiment comprised three treatments: (1) one-layer solar treatment without plastic sheeting and rotated one-third of a turn once a week; (2) two-layer solar treatment with plastic sheeting and no rotation; and (3) two-layer solar treatment without plastic sheeting and no rotation (fig. 1). The experiment lasted for 6 weeks; installed on 1–2 June 1999 and terminated on 19–20 July 1999. Logs in the one-layer with rotation treatment were rotated on 11 June, 18 June, 25 June, 1 July, and 9 July.

For the one-layer treatment, seven logs were arranged side by side on the ground. Logs in this treatment were rotated one-third of a turn once a week, so that by the end of the experiment all sides of the logs were fully exposed to the sun for approximately 2 weeks. Approximately one-third of the log surface was fully exposed to the sun at any given time. For the two-layer solar treatment with plastic sheeting, seven logs were stacked in two layers, with four logs on the lower layer and three on the upper layer, and the stack covered with 6-mill clear plastic sheeting. The plastic sheeting was sealed around the edges of the stack with soil. For the two-layer solar treatment without plastic sheeting, logs were arranged the same way as for the two-layer solar treatment with plastic sheeting but were not covered.

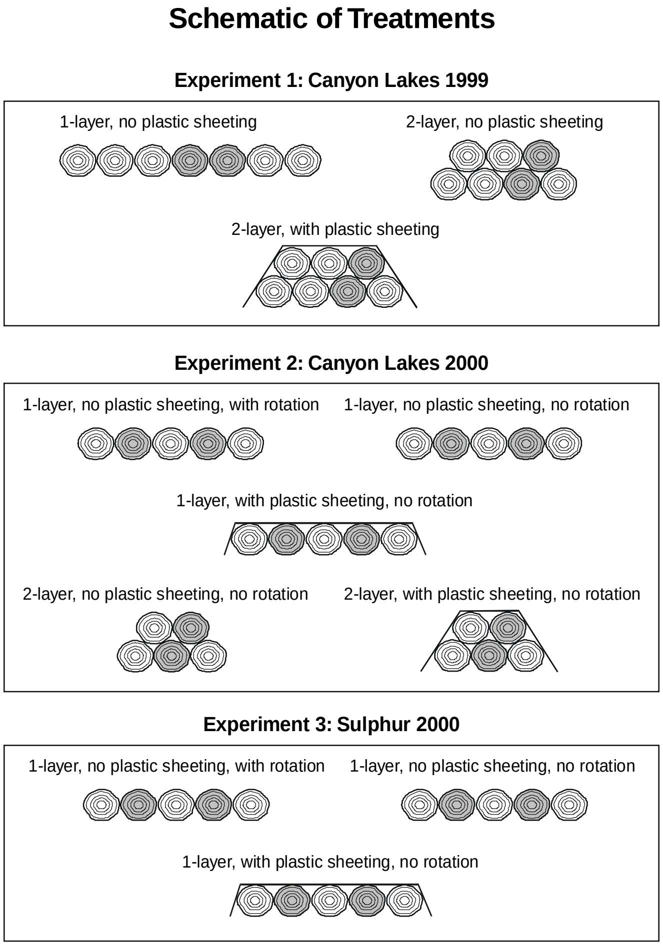

Figure 1. Schematics of treatments established in experiments 1 through 3. Circles indicate logs. Logs with shading indicate the position of the logs where temperature was monitored, Canyon Lakes and Sulphur Ranger Districts, Arapaho-Roosevelt National Forest, Colorado, May–July 1999–2000.

Table 1. Species treated, starting and termination dates, and locations for experiments 1 through 3, Canyon Lakes and Sulphur Ranger Districts, Arapaho and Roosevelt National Forests, Colorado. June–July 1999 and May–July 2000.

	Experiment 1	Experiment 2	Experiment 3
Species	*Pinus ponderosa*	*Pinus ponderosa*	*Pinus contorta*
Starting date	June 1–2, 1999	May 30–June 1, 2000	June 6–7, 2000
Termination date	July 19–20, 1999	July 10–12, 2000	July 5–6, 2000
Location	Canyon Lakes RD	Canyon Lakes RD	Sulphur RD

Experiment 2—This experiment incorporated two additional one-layer treatments to the treatments from experiment 1: a one-layer treatment with plastic sheeting and no rotation and a one-layer treatment without plastic sheeting no log rotation. This experiment also lasted for 6 weeks; installed on 30 May to 1 June 2000 and terminated on 10–12 July 2000. Logs in the rotated treatment were turned on 9 June, 16 June, 23 June, 29 June, and 3 July. For the one-layer treatments, five logs were arranged side by side on the ground; for the two-layer treatments five logs were stacked in two layers, with three logs on the lower layer and two on the upper layer.

Experiment 3—This experiment included only the one-layer treatments used in experiments 1 and 2 and lasted for 4 weeks; installed on 6–7 June 2000 and terminated on 5–6 July 2000. Logs in the rotated treatment were turned on 16 June and 26 June, so that by the completion date all sides were exposed to the sun for approximately 10 days. Five logs were used for each treatment. The logs were arranged side by side on the ground.

For all experiments, pines infested with mountain pine beetle were felled, limbed, and cut into 1.2 m (4 ft) logs. Average tree diameters ± standard error of the mean at breast height for the three experiments were as follows: experiment 1 — 31.9 ± 0.9 cm (12.5 ± 0.3 inches); experiment 2 — 34.8 ± 1.4 cm (13.7 ± 0.6 inches), and experiment 3 — 31.4 ± 0.9 cm (12.3 ± 0.4 inches). The north-facing aspect of each tree was marked prior to felling and then marked on the end of each log. The lower five to six logs were used from the felled trees because this is where mountain pine beetle infestations tend to concentrate. Logs were kept covered with branches to prevent overheating prior to pretreatment brood sampling. All logs were numbered with metal tags and information recorded on diameter of source tree at breast height and position of the log in the tree. Numbers ran sequentially starting from the bottom log, which was about 0.76 m (2.5 ft) from the ground. Logs less than 15.24 cm (6 inches) outside diameter were not used because that is about the smallest diameter where mountain pine beetles are likely to be found. Logs were distributed into stacks based on the diameter of the source tree at breast height and log location in order to create stacks of similar composition and to represent each source tree in multiple stacks. Each treatment was then randomly assigned to one of the stacks.

For consistency, logs were always placed with the north aspect oriented up and the south aspect oriented toward the ground, and these orientations will be referred to hereafter as top and bottom aspect, respectively. For the one-layer with rotation treatments, the north side began in the top orientation. Because rotation resulted in log orientation changes during the experiment, the north and south terminology is retained for this treatment only.

Four replications of each treatment were conducted for each experiment. The replications were within 3 miles of one another. All logs used for each replication came from the same group of infested trees. Each replication was in an area with a high degree of sun exposure, such as a canopy gap or small meadow, in proximity to the source area of the trees.

Brood Sampling

To evaluate the effectiveness of treatments, brood sampling was conducted in all logs before and after treatment. For each pre- and posttreatment sampling, two 15.2 X 30.5 cm (6 X 12 inches) samples with a surface area of 0.05 m^2 (0.5 ft^2) were collected from each log. One sample was taken from the north aspect and one from the south aspect and on opposite ends of each log. Live mountain pine beetle larvae (and a few pupae) were counted before treatment. At the conclusion of the experiment, two additional 15.2 X 30.5 cm (6 X 12 inches) samples were collected, again one each from the north and south sides and on opposite ends of each log, to determine the number of live mountain pine beetle immature or brood adult per 0.05 m^2 (0.5 ft^2) of bark surface. Hereafter, these counts will be referred to as pretreatment and posttreatment brood densities.

Temperature Monitoring

Temperature monitoring and recording equipment was set up for one replicate of each experiment. Temperature data were collected for all treatments in the replicate by placing YSI thermilinear thermistor networks into the inner bark in the top and bottom of one or two logs in each treatment. The thermistors were connected to a Campbell Scientific 21X micrologger (Logan, UT). A temperature reading was taken every minute, and hourly averages were stored by the micrologger. From these data we obtained the maximum hourly average per day (hereafter referred as maximum temperature). The equipment was set on 4 June 1999 for experiment 1; 2 June 2000 for experiment 2; and 6 June 2000 for experiment 3. Thermistors in the one-layer treatment with rotation were reset in the top and bottom of the log when the log was turned weekly.

Phloem Moisture Analysis

While conducting posttreatment brood sampling for experiment 1 in 1999, we noticed that logs in the one-layer with rotation treatment appeared to be much drier than in the rest of the treatments. We hypothesized that drying of the phloem may have contributed to reduced insect survival and decided to examine this further. In experiment 2, we felled an uninfested tree for each replicate. The tree was also cut into 1.2 m (4 ft) logs. An 8.9 X 8.9 cm (3.5 X 3.5 inch) phloem sample was collected from the north and the south aspect of each log, just as was done with the brood sampling. After the phloem samples were collected, the logs were randomly assigned to the different treatments. One log was placed in each of the one-layer treatments. Two logs were placed in each of the two-layer treatments, one each on the upper and lower layers.

The outer bark was removed from each sample and the phloem wrapped in aluminum foil, placed in a cooler, and brought to the laboratory. The samples were weighed and the sample area measured using video imaging (Delta-T Devices, Cambridge, England) and sample thickness measured with a caliper. The samples were dried in an oven at 65 °C (149 °F) for 48 hours and dry weight obtained. Moisture content was calculated in a dry weight basis (mg H_2O/gm dry weight of phloem tissue). After drying, the samples were weighed again. With this information, we calculated percent moisture content based on dry weight. Volume of the fresh sample was also calculated. This process was repeated after completion of the study to obtain posttreatment data on the same variables.

Data Analysis

When planning for experiments 2 and 3, we were faced with a considerable increase in the number of samples needed to adequately measure pre- and posttreatment brood densities. The observed data collected in experiment 1 were assumed to represent the target population. Using these data, a bootstrap resampling simulation was conducted to assess the possible bias and loss of precision associated with reduced sample sizes (Efron and Tibshirani 1993). Hypothetical samples were drawn with replacement from the observed 1999 data and an estimate of the mean and associated standard error obtained for each sample. A total of 1,000 samples were drawn for each sampling level of n=3 to n=7. The distribution of the estimates and standard errors were then displayed using box plots. The potential for bias and lack of precision associated with particular sample sizes can be assessed by noting whether the mean hypothetical estimate is close to the observed estimate in 1999, whether the box is symmetric about the "true" estimate, the length of the box (which includes 50 percent of the hypothetical estimates), and the size of potential large deviations from the "true" estimate as represented by the length of the whiskers and presence of individual outliers. The analysis indicated that using five logs per stack would be adequate. Therefore, in experiments 2 and 3, all stacks used contained five logs. The rest of the methodology was the same as in experiment 1.

Repeated measures analysis of variance was used to examine differences between pre- and posttreatment brood densities. Deviations from normality in brood differences were examined with Q-Q plots and the Kolmogorov-Smirnov test for normality. The test indicated no deviations from normality for any of the experiments. Treatment and aspect main effects and their interactions were examined. To examine the effect of layer in the stack, a separate analysis was conducted where only the two-layer treatments were included. Tukey's HSD test was used to evaluate differences when comparing three or more means. Because we measured live mountain pine beetle densities before and after treatment, larger differences are associated with decreased survival.

Repeated measures analysis of variance was also conducted to examine differences in moisture content of the uninfested logs before and after treatment in experiment 2. Because of the variability caused by variations in sample dimensions and phloem thickness, the dry weight on a volume basis of the samples was used as a covariate.

Maximum temperature data were examined with analysis of variance to determine if significant variation was associated with treatments, aspects, layers, and aspect within layers. A paired t-test was conducted to compare pretreatment brood densities between the north and the south aspect of the logs.

Results

Experiment 1

In experiment 1, the difference between pre- and posttreatment brood densities was significantly larger (indicating reduced survival) in the one-layer with rotation treatment when compared to the two-layer with no plastic sheeting treatment, but it was not different from the two-layer with plastic sheeting treatment (table 2A).

Mean differences in brood densities associated with aspect were observed only in the two-layer with plastic sheeting treatment where reduced survival was observed in the top aspect of the logs. There were no mean differences in brood densities detected between layers for the two-layer treatments (table 2B). Survival was significantly reduced in the top aspects of both layers of the two-layer with plastic sheeting, but no differences were observed in aspects within layers for the two-layer with no plastic sheeting treatment (table 2C).

Maximum temperatures were significantly higher in the upper layer (40.9 ± 1.6 °C) of the two-layer with plastic sheeting treatment when compared to the upper layer of the two-layer with no plastic treatment (25.1 ± 1.0 °C) and the one-layer with rotation treatment (26.1 ± 0.9 °C) (not shown in table). Maximum temperatures were significantly higher in the top aspect of the logs in the one-layer treatment (table 3B). For the two-layer treatments only, maximum temperatures were higher in the treatment with plastic sheeting, the top aspect of the logs, and in the upper layers (table 3C). For the aspect and layer effect by two-layer treatments, maximum temperatures were higher in the top aspects of both two-layer treatments, and in the upper layer of the two-layer with plastic sheeting treatment (table 3D). For the aspect within layer effect by two-layer treatments, for both treatments there were higher maximum temperatures in the top aspects of both layers (table 3E).

Experiment 2

Although survival was less in the one-layer with rotation treatment, differences between pre- and posttreatment brood densities were not significant among any of the treatments

Table 2. Mean (standard error of mean) pretreatment, posttreatment, and difference in brood densities per 0.05 m^2 (0.5 ft^2) for treatments, aspects, and layers in experiment 1, Canyon Lakes Ranger District, Arapaho and Roosevelt National Forests, Colorado. June–July 1999.

		Pretreatment brood density	Posttreatment brood density	Mean difference[a]
A. Treatment main effect				
1-layer with rotation		40.6 (3.0)	0.6 (0.3)	39.9 (3.0) a
2-layer with plastic sheeting		37.5 (3.5)	7.5 (1.6)	30.0 (3.7) ab
2-layer no plastic sheeting		35.4 (3.1)	14.2 (2.6)	21.2 (3.8) b
B. Aspect and layers effects by treatments				
1-layer with rotation	North	43.9 (4.1)	1.1 (0.5)	42.8 (4.2) a
	South	37.2 (4.2)	0.1 (0.1)	37.1 (4.3) a
2-layer with plastic sheeting	Top	45.4 (4.9)	2.3 (1.1)	43.1 (4.5) a
	Bottom	29.6 (4.6)	12.7 (2.8)	16.9 (4.8) b
	Upper	33.0 (5.5)	4.2 (2.2)	28.8 (6.2) a
	Lower	40.9 (4.5)	10.0 (2.3)	30.8 (4.6) a
2-layer no plastic sheeting	Top	38.3 (4.7)	10.1 (3.2)	28.2 (5.8) a
	Bottom	32.5 (4.1)	18.4 (3.9)	14.1 (4.5) a
	Upper	30.5 (3.7)	5.2 (1.6)	25.3 (3.4) a
	Lower	39.0 (4.7)	21.0 (4.0)	18.0 (6.1) a
C. Aspects within layers for two-layer treatments				
2-layer with plastic sheeting	Upper:top	43.6 (7.1)	0.1 (0.1)	43.5 (7.1) a
	Upper:bottom	22.4 (7.6)	8.3 (4.2)	14.2 (8.5) b
	Lower:top	46.8 (6.9)	4.0 (1.8)	42.8 (6.0) a
	Lower:bottom	35.0 (5.5)	16.1 (3.6)	18.9 (5.7) b
2-layer no plastic sheeting	Upper:top	32.5 (5.8)	3.2 (2.4)	29.3 (4.9) a
	Upper:bottom	28.5 (4.8)	7.2 (2.1)	21.3 (4.5) a
	Lower:top	42.6 (7.1)	15.3 (5.0)	27.4 (9.6) a
	Lower:bottom	35.4 (6.2)	26.8 (6.0)	8.7 (7.0) a

[a] Treatment, aspect, layer, and aspect within layer mean difference within each treatment followed by the same letter are not significantly different at the P = 0.05 level. ANOVA for two means and Tukey's HSD test for more than two means. Except for treatment means, comparisons are made between pairwise indented effects.

(table 4A). Mean differences between pre- and posttreatment brood densities indicate that for all treatments there was significantly less survival in the top aspects and in the north aspect of the one-layer with rotation treatment. For the two-layer treatments there were no mean differences in brood densities detected between layers (table 4B). For the two-layer treatment with plastic sheeting, there was also reduced survival in the top aspect of the upper layer of logs. No mean differences in brood densities were observed in aspect within layers for the lower layer of the two-layer with plastic sheeting treatment or for any layer of the two-layer with no plastic sheeting treatment (table 4C).

Temperature data for the one-layer treatments indicated higher maximum temperatures for the one-layer with plastic sheeting treatment and higher maximum temperatures in the top aspects across all treatments (table 3A). The top aspects in the one-layer treatments also had higher maximum temperatures for all treatments (table 3B). For the two-layer treatments, higher maximum temperatures were observed in the two-layer with plastic sheeting treatment, in the top aspects, and in the upper layer across all two-layer treatments (table 3C). For the aspect and layer effects for the two-layer treatments: for the two-layer with plastic sheeting treatment, higher maximum temperatures were observed in the top aspects and in the upper layer; for the two-layer no plastic sheeting treatment, no differences in maximum temperatures were observed for the aspect effect but higher maximum temperatures were observed in the upper layer (table 3D). For the aspect within layer by two-layer treatments, higher maximum temperatures were observed in the top aspect of both layers for the two-layer with plastic sheeting treatment but no differences were observed for aspect within layer for the two-layer no plastic sheeting treatment (table 3E).

Phloem Moisture Analysis—Repeated measures analysis of variance indicated no mean differences in phloem moisture content across time (before and after treatment) (F = 0.71; df = 1, 15; P > 0.41), or treatment by time (F = 0.53; df = 4, 15; P > 0.71), or aspect by time (F = 0.0; df = 1, 15; P > 0.99). Overall pretreatment and posttreatment means (standard error of the mean) for moisture content across all treatments, aspects, and layers were 117.8 (1.8) and 142.2 (5.6), respectively.

Table 3. Mean (standard error of mean) daily maximum hourly average recorded in experiments 1 through 3 for treatments, aspects, and layers, Canyon Lakes and Sulphur Ranger Districts, Arapaho and Roosevelt National Forests, Colorado. June–July 1999 and May–July 2000. [a]

	Experiment 1	Experiment 2	Experiment 3
A. Treatment and aspect main effects			
1-layer rotated	26.1 (0.9)	33.0 (1.3) b	28.1 (1.4) b
1-layer with plastic sheeting	NA	40.0 (1.4) a	37.6 (2.0) a
1-layer no rotation	NA	31.3 (1.3) b	29.3 (1.5) b
Top	NA	49.3 (0.7) a	47.9 (0.9) a
Bottom	NA	20.2 (0.4) b	15.4 (0.3) b
B. Aspect main effect by treatments			
1-layer rotated			
Top	36.5 (1.0) a	46.1 (1.2) a	41.4 (1.1) a
Bottom	15.7 (0.5) b	19.9 (0.9) b	14.8 (0.8) b
1-layer with plastic sheeting			
Top	NA	55.9 (1.2) a	58.0 (1.2) a
Bottom	NA	24.2 (0.3) b	17.3 (0.3) b
1-layer no rotation			
Top	NA	45.9 (1.1) a	44.3 (1.1) a
Bottom	NA	16.6 (0.3) b	14.2 (0.4) b
C. Two-layer treatments only: treatment, aspect, and layer main effects			
2-layer with plastic sheeting	32.5 (1.1) a	36.3 (1.2) a	NA
2-layer no plastic sheeting	24.3 (0.8) b	33.7 (1.4) b	NA
Top	37.4 (0.9) a	40.1 (1.4) a	NA
Bottom	19.4 (0.5) b	30.0 (1.4) b	NA
Upper	33.0 (1.1) a	46.2 (1.2) a	NA
Lower	23.8 (0.8) b	23.8 (0.6) b	NA
D. Two-layer treatments by treatments: aspects and layer effects			
2-layer with plastic sheeting			
Top	41.6 (1.5) a	46.5 (1.8) a	NA
Bottom	23.4 (0.8) b	26.1 (0.6) b	NA
Upper	40.9 (1.6) a	43.7 (2.0) a	NA
Lower	24.0 (0.8) b	28.9 (0.8) b	NA
2-layer no plastic sheeting			
Top	33.2 (0.9) a	33.6 (1.9) a	NA
Bottom	15.5 (0.5) b	33.9 (2.1) a	NA
Upper	25.1 (1.0) a	48.7 (1.4) a	NA
Lower	23.6 (1.3) a	18.7 (0.4) b	NA
E. By treatment and layer: aspect effect			
2-layer with plastic sheeting			
Upper:top	53.0 (1.7) a	58.6 (2.0) a	NA
Upper:bottom	28.9 (0.8) b	28.7 (0.8) b	NA
Lower:top	30.1 (0.9) a	34.3 (0.9) a	NA
Lower:bottom	17.9 (0.5) b	23.5 (0.7) b	NA
2-layer no plastic sheeting			
Upper:top	31.9 (1.2) a	47.7 (1.8) a	NA
Upper:bottom	18.3 (0.7) b	49.8 (2.1) a	NA
Lower:top	46.9 (1.3) a	19.6 (0.7) a	NA
Lower:bottom	12.7 (0.5) b	17.9 (0.5) a	NA

[a] Means within columns by and indentation level followed by the same letter are not significantly different at the P = 0.05 level. NA means treatment not in that experiment. ANOVA for two means and Tukey’s HSD test for more than two means.

Table 4. Mean (standard error of mean) pretreatment, posttreatment, and difference in brood densities per 0.05 m^2 (0.5 ft^2) for treatments, aspects, and layers in experiment 2, Canyon Lakes Ranger District, Arapaho and Roosevelt National Forests, Colorado. June–July 2000.

		Pretreatment brood density	Posttreatment brood density	Mean difference[a]
A. Treatment main effect				
1-layer with rotation		37.7 (5.1)	0.7 (0.4)	37.0 (5.1) a
1-layer with plastic sheeting		31.0 (3.7)	5.7 (1.6)	25.3 (4.4) a
1-layer with no rotation		41.8 (4.7)	10.3 (3.2)	31.5 (6.2) a
2-layer with plastic sheeting		35.8 (3.9)	7.0 (2.3)	28.8 (4.2) a
2-layer no plastic sheeting		36.3 (3.9)	12.0 (2.8)	24.3 (4.2) a
B. Aspect and layer effects by treatment				
1-layer with rotation	North	50.3 (8.2)	0.3 (0.2)	50.1 (8.2) a
	South	25.1 (4.6)	1.1 (0.7)	24.0 (4.5) b
1-layer with plastic sheeting	Top	37.9 (6.2)	0.0 (0.0)	37.9 (6.2) a
	Bottom	24.1 (3.8)	11.4 (2.7)	12.7 (4.8) b
1-layer no rotation	Top	56.1 (6.1)	0.0 (0.0)	56.1 (6.1) a
	Bottom	27.4 (5.8)	20.6 (5.5)	6.8 (7.5) b
2-layer with plastic sheeting	Top	44.9 (6.4)	7.5 (4.2)	37.4 (7.3) a
	Bottom	26.8 (3.8)	6.5 (2.1)	20.3 (3.5) b
	Upper	38.3 (7.2)	2.3 (1.1)	36.0 (7.4) a
	Lower	34.1 (4.6)	10.1 (3.7)	24.0 (4.9) a
2-layer no plastic sheeting	Top	43.7 (5.9)	8.1 (3.6)	35.6 (6.1) a
	Bottom	28.8 (4.5)	15.9 (4.3)	12.9 (4.7) b
	Upper	33.9 (7.7)	6.9 (3.2)	26.9 (8.1) a
	Lower	37.8 (4.0)	15.4 (4.1)	22.5 (4.6) a
C. Aspect within layer for two-layer treatments				
2-layer with plastic sheeting	Upper:top	52.6 (11.0)	0.1 (0.1)	52.5 (11.0) a
	Upper:bottom	24.0 (6.7)	4.5 (1.9)	19.5 (6.2) b
	Lower:top	39.7 (7.7)	12.4 (6.8)	27.3 (8.9) a
	Lower:bottom	28.6 (4.7)	7.8 (3.3)	20.8 (4.4) a
2-layer no plastic sheeting	Upper:top	42.0 (12.7)	0.0 (0.0)	42.0 (12.7) a
	Upper:bottom	25.8 (8.7)	13.9 (5.6)	11.9 (7.5) a
	Lower:top	44.8 (5.7)	13.5 (5.5)	31.3 (5.9) a
	Lower:bottom	30.8 (5.1)	17.3 (6.3)	13.6 (6.2) a

[a] Treatment, aspect, layer, and aspect within layer mean difference within each treatment followed by the same letter are not significantly different at the P = 0.05 level. ANOVA for two means and Tukey's HSD test for more than two means. Except for treatment means, comparisons are made between pairwise indented effects.

Experiment 3

We observed reduced survival in the one-layer with rotation treatment, but mean differences in brood densities were not significant among any of the treatments (table 5A). Mean differences in brood densities indicated significantly reduced survival in the north aspect of the one-layer with rotation treatment and in the top aspects of the one-layer with plastic sheeting and the one-layer with no rotation treatment (table 5B).

Temperature data indicated higher maximum temperatures for the one-layer with plastic sheeting treatment and the top aspect across all treatments (table 3A). For each treatment the top aspects had higher maximum temperatures (table 3B).

Pretreatment Brood Densities by Aspect

In all experiments pretreatment brood densities per 0.05 m^2 (0.5 ft^2) of bark surface were significantly higher in the north aspect of the logs compared to the south (experiment 1, $t = 3.3$, $df = 83$, $P < 0.001$; experiment 2, $t = 6.6$, $df = 98$, $P < 0.0001$; experiment 3, $t = 8.7$, $df = 58$, $P < 0.0001$). Mean pretreatment brood densities (standard error of the mean) in experiment 1 were 42.5 (2.6) for the north aspect and 33.1 (2.5) for the south aspect. In experiment 2, average densities were 46.5 (2.9) for the north aspect and 26.4 (2.0) for the south aspect. For experiment 3 the mean brood densities were 49.3 (3.2) in the north aspect and 20.0 (2.4) in the south aspect.

Discussion

Seasonal trends of mountain pine beetle in the Black Hills, South Dakota, indicated that brood densities declined precipitously shortly after the trees were attacked and the brood established (Schmid 1972). Conversely, little change in brood densities occurred after late May. Therefore, we believe that the pretreatment brood densities obtained in our study represent potentially emerging populations and that the subsequent reductions observed in posttreatment brood densities satisfactorily characterize treatment effects.

All treatments in all experiments for both tree species and across all aspects and layers caused drastic reductions in mountain pine beetle survival in the infested logs. The highest treatment survival observed was 40 percent for the two-layer with no plastic sheeting in experiment 2. The one-layer with rotation treatment was significantly better than one other treatment evaluated only in experiment 1. In experiments 2 and 3, the one-layer with rotation treatments had the largest reductions in brood counts, but the differences were not significant. In all experiments, brood densities were consistently lower after treatment in the top aspects of the treated logs.

With some exceptions, higher maximum temperatures were observed in the top aspects of the logs, in the upper layers of the two-layer treatments, and in the treatments covered with plastic sheeting. These higher maximum temperatures were associated with reduced mountain pine beetle survival in the top aspects of the logs and the upper layers of the two-layer treatments but not in the two-layer treatments with plastic sheeting.

The lack of differences in phloem moisture before and after treatment in experiment 2 suggests that observed reductions in brood survival may primarily be a function of increased temperature. This statement needs to be cautioned. We examined phloem moisture in uninfested trees because it is difficult to obtain an adequate sample for moisture content analysis from an infested tree. The uninfested tree is different from the infested tree, which has been losing moisture from the time that it dies from beetle attack soon after infestation in the summer. In standing infested trees, moisture loss is not a limiting factor for mountain pine beetle populations as evidenced by their natural emergence from such trees. However, a felled infested tree has more tree surface area directly exposed to radiation, so phloem drying beyond some threshold may become an important factor by itself or in combination with high temperature.

Mitchell and Schmid (1973) conducted a laboratory study and indicated that inner bark temperatures of 49 °C (120 °F) for 30 minutes caused 92 percent mortality of spruce beetle in 5 ft logs, while inner bark temperatures of 46.1 °C (115 °F) caused 83 percent mortality. Mitchell and Schmid (1973) recognized that, within the range of temperatures examined, temperature levels were important in determining mortality levels. Nevertheless, they suggested that the duration of specific high temperatures was more important than the temperature itself.

Our study was not designed with the intent of identifying temperature thresholds that may be responsible for causing mortality. Nevertheless, mountain pine beetle survival appears related to maximum bark temperatures. When maximum temperatures reached or surpassed 40 °C (104 °F), observed survival was less than 10 percent with only two exceptions: in experiment 1 in the top aspect of the lower layer for the two-layer with no plastic sheeting treatment, and in experiment 2 in the top aspect of the lower layer of the two-layer with plastic sheeting treatment. When the maximum temperature failed to reach 40 °C (104 °F), then survival was consistently over 20 percent with one exception: the bottom aspect of the upper layer for the two-layer with plastic sheeting in experiment 2 (table 6). This critical temperature observed in our study is not unreasonably different from the lethal temperatures obtained by Mitchell and Schmid (1973).

Management Considerations

Mountain pine beetle most commonly infests the lower 20 to 30 ft of a tree. Felling and bucking an infested tree about 12 inches d.b.h. into 4 ft logs will yield about five to seven logs for treatment. Under epidemic populations of mountain pine

Table 5. Mean (standard error of mean) pretreatment, posttreatment, and difference in brood densities per 0.5 ft^2 (0.05 m^2) for treatments and aspects in experiment 3, Sulphur Ranger District, Arapaho and Roosevelt National Forests, Colorado. May–July 2000.

		Pretreatment brood density	Posttreatment brood density	Mean difference[a]
A. Treatment main effect				
1-layer with rotation		36.5 (4.6)	5.33 (2.5)	31.2 (4.5) a
1-layer with plastic sheeting		33.5 (4.0)	13.1 (3.8)	19.7 (5.2) a
1-layer no rotation		35.0 (4.0)	10.4 (2.8)	24.7 (5.3) a
B. Aspect effect by treatment				
1-layer with rotation	North	52.9 (6.4)	8.2 (4.8)	44.8 (7.2) a
	South	20.1 (4.1)	2.5 (1.4)	17.6 (3.3) b
1-layer with plastic sheeting	Top	45.8 (5.1)	1.8 (1.8)	43.7 (6.4) a
	Bottom	21.3 (5.0)	23.2 (6.2)	-1.9 (4.0) b
1-layer no rotation and no plastic sheeting	Top	50.6 (5.2)	1.8 (0.6)	48.9 (5.2) a
	Bottom	18.6 (3.4)	18.9 (4.9)	-0.8 (4.4) b

[a] Treatment and aspect mean difference within each treatment followed by the same letter are not significantly different at the P = 0.05 level. ANOVA for two means and Tukey's HSD test for more than two means. Except for treatment means, comparisons are made between pairwise effects.

Table 6. Percent brood survival of *Dendroctonus ponderosae* and corresponding maximum temperature (°C) recorded for the particular surface within treatment for experiments 1 through 3, Canyon Lakes and Sulphur Ranger Districts, Arapaho and Roosevelt National Forests, Colorado. June–July 1999 and May–July 2000.

			Survival (%)[a]	Max Temp (°C)
Experiment 1	2-layer with plastic sheeting	Upper:top	0.2	66.7
		Upper:bottom	36.8	38.6
		Lower:top	8.6	40.3
		Lower:bottom	45.9	27.4
	2-layer with no plastic sheeting	Upper:top	9.8	44.1
		Upper:bottom	25.2	29.7
		Lower:top	35.8	46.9
		Lower:bottom	75.5	25.4
Experiment 2	2-layer with plastic sheeting	Upper:top	0.2	73.3
		Upper:bottom	18.8	38.1
		Lower:top	31.3	42.9
		Lower:bottom	27.4	30.8
	2-layer with no plastic sheeting	Upper:top	0.0	62.6
		Upper:bottom	53.9	na[b]
		Lower:top	30.1	26.7
		Lower:bottom	56.0	25.2
	1-layer with plastic sheeting	Top	0.0	69.6
		Bottom	70.9	32.6
	1-layer no plastic sheeting	Top	0.0	62.2
		Bottom	47.2	23.4
Experiment 3	1-layer with plastic sheeting	Top	4.0	70.4
		Bottom	100	25.1
	1-layer no plastic sheeting	Top	3.5	57.0
		Bottom	100	27.7

[a] Percent survival calculated as ratio of posttreatment brood density to pretreatment brood density for the particular surface within treatment. Table presents treatments with no rotation only.

[b] Thermistor malfunction.

beetle, where groups of five to hundreds of trees are common, the number of logs to be treated can become overwhelming. Solar treatments may be appropriate only with small groups in high value areas.

If plastic sheeting is used to cover stacks of logs, the number of trees that can be treated with one roll of plastic sheeting will vary. A 10 x 100 ft roll of 6 mil clear plastic sheeting costs about $35 and weighs about 30 lb. If 4 ft logs are arranged in stacks of five to seven logs, a roll may be enough for about 10 stacks, for a cost of about $3.50 per stack.

The use of plastic sheeting presents additional challenges. When the treatments are complete, there is the need to responsibly dispose of the plastic sheeting. We observed ant nests inside of most stacks treated with plastic sheeting, probably due to increased humidity and perhaps protection from predators. The ants become problematic in the process of removing and disposing of the plastic sheeting.

In our study, the use of two-layer treatments was as effective statistically as the one-layer treatments in experiments 2 and 3. However, survival increased from the top to the bottom of a log and from the upper layer to the lower layer in the stacks. Although, three or more layers were not tested in our study, we suspect that lethal temperatures may not be reached beyond the second layer of logs from the top of the stack. If this is the case, stacks more than two-layers high may not effectively reduce mountain pine beetles in the infested logs.

The one-layer treatments without plastic sheeting seem to present the best alternative from the perspective of reduced cost and not having to dispose of plastic sheeting. Although overall survival in the one-layer treatments without plastic sheeting was not different between rotated and unrotated treatments, significantly increased survival was observed in the underside of the unrotated treatments in experiments 2 and 3. A manager or homeowner that has the time and resources to turn the logs to expose the different surfaces to the sun may derive some benefits by reducing beetle survival.

In all experiments, logs contained higher brood densities in the north aspect of the tree compared to the south. This is consistent with observations made by McCambridge (1964). If logs are not to be rotated, the north aspect should face the sun to expose a larger proportion of the brood to direct solar radiation. If rotation is to be conducted, the user may want to plan so that the north aspect is facing the sun during the warmest time during the treatment.

When using solarization, duration of the treatments is important. The experiments conducted at the Canyon Lakes Ranger District represent conditions in Colorado Front Range ponderosa pine forests. The experiments lasted for 6 weeks, which seemed an adequate time to cause reduced survival of mountain pine beetle brood. While we established our treatments the last week of May and first week of June, a land manager or homeowner will likely see benefits by installing treatments earlier in the spring or even in the fall after beetle flight, if a trained professional can adequately identify successfully attacked trees. On the other hand, the experiment conducted at the Sulphur Ranger District in a lodgepole pine forest lasted for only 4 weeks because logistics prevented an earlier establishment date, which would have been more desirable. In addition, it was important to terminate the experiment before the initiation of beetle flight to preserve the accuracy of posttreatment brood counts. Had the treatments been in place for a longer period, further reductions in survival may have been observed. We also observed cool temperatures during part of that study.

Lodgepole pine forests are not as warm as Front Range ponderosa pine forests because of elevation and because of higher canopy closure. In lodgepole pine forests treatments should last longer than what we were able to complete. Because snow may impede accessibility to some sites in the spring, it may be advisable to establish treatments in the fall after beetle flight is complete but only after careful determination of the success of new attacks.

Solarization treatments should always be established in areas that will facilitate the highest temperatures possible. Forest openings, particularly with southern exposures, should be favored. Finding openings in Front Range ponderosa pine forests is not difficult but may be challenging in higher elevation lodgepole pine forests. Removing additional trees in lodgepole pine forests may be necessary to increase solar radiation in the treatment area.

The information provided should help guide the use of solar treatments for reducing survival of mountain pine beetles in infested ponderosa and lodgepole pine logs in Colorado. Properly implemented solar treatments will reduce mountain pine beetle survival in infested logs.

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