



Full length article

Factors influencing pine engraver (*Ips pini* Say) colonization of ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws.) slash in Northern Arizona

Christopher J. Hayes^{a,*}, Tom E. DeGomez^a, Joel D. McMillin^b,
John A. Anhold^b, Richard W. Hofstetter^c

^a University of Arizona, School of Natural Resources, NAU Box 15018, Flagstaff, AZ 86011-15018, United States

^b USDA Forest Service, Southwestern Region, Forestry and Forest Health, Arizona Zone, 2500 S. Pine Knoll Drive, Flagstaff, AZ 86001-6381, United States

^c Northern Arizona University, School of Forestry, NAU Box 15018, Flagstaff, AZ 86011, United States

ARTICLE INFO

Article history:

Received 14 June 2007

Received in revised form 19 February 2008

Accepted 23 February 2008

Keywords:

Ips pini

Light intensity

Log size

Pinus ponderosa

Slash management

Thinning date

ABSTRACT

Thinning projects have increased in recent years to reduce standing fuels and fire hazard within the Wildland Urban Interface (WUI) and to improve general forest conditions through forest health restoration treatments. As a consequence, large volumes of thinning slash have been generated, increasing the potential for growth of bark beetle (*Ips* spp.) populations. Because slash can initiate outbreaks in standing trees, a critical examination of slash management guidelines is needed to minimize bark beetle impacts associated with thinning treatments. Specifically, we examined effects of season of slash cutting, sunlight intensity (stand density) and log size on pine engraver (*Ips pini* Say) reproduction in North-central Arizona, USA. Ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws.) trees were felled and cut to 16 sizes (diameters of 10, 15, 20, and 25 cm and lengths of 15, 30, 45, and 60 cm) in October, January, April and July, for 2 years. The 16 logs of differing size were placed in groups in overstory stand densities of 5, 14, and 27.5 m²/ha (representing high, partial, and low sunlight levels). Response variables included attack density, emergence density, and beetle population growth rate. Log length had a positive relationship with both attack and emergence density. Log diameter had a significant effect on attack and emergence density, with a preference shown for intermediate diameter bolts. During a year with above average winter precipitation, cutting date and the interaction of cutting date and light level had significant effects on attack density. Fewer beetles attacked both bolts that had been exposed for longer periods of time and logs exposed to high sunlight levels. Cutting date, and the interaction of cutting date and light level, influenced emergence density, but light level alone did not. Emergence density was lowest in spring-cut logs in both years. Cutting date also had an effect on beetle population growth rate, with fall-cut logs having the highest population growth, while light level had no effect. Extended time-since-cutting (e.g. fall cutting), high light levels and small log diameter did not consistently cause reductions in beetle attack and reproductive performance as was hypothesized. Implications of these results for slash management guidelines are discussed.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

Long-term fire suppression policy has led to the buildup of forest fuels and stand densities in ponderosa pine forests, increasing the potential for high severity wildfire (Covington and Moore, 1994). Recent large fires, and the loss of life and property caused by these fires, have led to changes in forest management policy, implemented under the National Fire Plan and Healthy Forests Restoration Act of 2003. Management

activities aimed at the reduction of hazardous fuels include mechanical thinning, prescribed fire, herbicide, grazing or a combination of these and other methods (National Fire Plan, 2000). In the southwest US, small diameter trees, branches, and tops of larger trees cut in these treatments are often piled on site for burning at a later date and serve as potential material for bark beetle reproduction.

Thinning stands to reduce fuels is an important management activity, but the creation of slash has potential hazards (Fettig et al., 2007); improper slash management has been blamed for causing buildups of pine engraver beetles, *Ips pini* (Say) and other *Ips* species (Kennedy, 1969; Schenk and Benjamin, 1969; Parker, 1991). The pine engraver is an important bark beetle with a wide

* Corresponding author. Tel.: +1 928 556 2101; fax: +1 928 556 2130.
E-mail address: chayes@email.arizona.edu (C.J. Hayes).

distribution throughout North American coniferous forests (Furniss and Carolin, 1977). It is considered moderately aggressive and typically attacks recently dead or weakened trees (Kegley et al., 1997), but can become more aggressive when population levels increase, attacking and killing live trees.

Pine engraver beetles are attracted to and regenerate in slash created during logging operations, and thinning and restoration treatments (Sartwell, 1970; Livingston, 1979; Parker, 1991; Gara et al., 1999). Known to initiate spring flights as early as mid March (Gaylord et al., 2008; Williams et al., 2008), offspring of early-spring fliers emerge from logging slash in late spring/early summer. This generation is thought to present the greatest threat to live standing trees, often causing mortality in residual trees.

Slash management has long been recognized as an appropriate tool for reducing *Ips* attacks on residual trees after thinning forest stands (Craighead, 1927; Fellin, 1980; Struble and Hall, 1955; Six et al., 2002). Current guidelines include separating slash production in time and space; generating slash during periods of beetle inactivity; limiting the size of treatment blocks; and treating slash through solarization, burning, burying, chipping, and direct removal from the site (Livingston, 1979; Parker, 1991; Gara et al., 1999; Fettig et al., 2006). Questions still remain regarding what is the most effective and economically feasible slash treatment for prevention of *Ips* build ups in ponderosa pine. Many of these strategies are based on anecdotal evidence and limited studies, or restricted to certain geographic locations.

Phloem moisture content and thickness are the main limiting factors to *Ips* development within logs (Anderson, 1948; Haack et al., 1984, 1987), and phloem condition should be affected by actions suggested in slash management guidelines. Among slash management techniques, scattering logging debris in open areas to promote rapid drying has been recommended to reduce the risk of pine engraver outbreaks (Livingston, 1979). In a study conducted in Northern Arizona, ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) logs exposed to high levels of sunlight were colonized less by pine engraver than logs exposed to medium and low sunlight levels and experienced low net brood production (Villa-Castillo and Wagner, 1996). Explanations for reduced colonization densities included reduction in pheromone production by attacking males caused by deterioration of phloem condition, and disruption of pheromone communication due to changes in microclimate (Villa-Castillo and Wagner, 1996). Temperature and wind speed has also been found to increase after forest thinning and aid in pine engraver dispersal (Hindmarch and Reid, 2001).

Recommendations vary as to the best time of the year to thin forests in order to reduce pine engraver (and other *Ips* species) population increases in slash. Most recommendations are for thinning to be conducted from July through December or January (Massey and Parker, 1981; DeGomez and Young, 2002). Fettig et al. (2006) found greater attacks by *Ips* and *Dendroctonus* on residual ponderosa pine in thinned plots during spring treatments compared to late summer or early fall in Arizona and California. Subsequent remeasurement of plots found that slash management treatments implemented in spring versus late summer resulted in significantly higher levels of tree mortality (DeGomez et al., 2008). Gara et al. (1999), in a study conducted in south-eastern Montana, found that winter logging provides suitable host material for spring beetle flight. Studies by Buckhorn (1957) demonstrated that ponderosa pine mortality caused by pine engraver in Oregon was greatest when slash was generated between February and July compared with August through January. However, with the exception of the Fettig et al. (2006) study, field tests on the effect of cutting date have not been conducted in the Southwest, and management recommendations remain based mostly on research conducted in other regions (e.g. Sartwell, 1970) or largely anecdotal evidence.

Current slash management guidelines also recommend removal or treatment of all slash >10 cm in diameter (Wilkinson and Foltz, 1982; Parker, 1991). In studies performed near Flagstaff, Arizona, pine engravers were found to successfully attack bolts 5 cm in diameter (Steed and Wagner, 2004). However, fewer of the smaller diameter bolts were attacked when compared to the 10 and 20 cm diameter pieces. When only attacked logs were evaluated, neither diameter nor length (choice of 60, 120 and 240 cm) affected attack, brood development, or emergence phases of colonization. Only at the very ends of the cut logs did phloem desiccation appear to have a potential negative effect on pine engraver colonization. In a lower elevation site in Arizona, both pine engraver and Arizona fivespined *Ips* (*Ips lecontei* Swaine) infesting small diameter material had reproductive success rates insufficient to cause population increase (Wesley, 1995). When length was evaluated, the intermediate length of 120 cm was preferred over 60 or 240 cm. In neither study were logs of less than 60 cm tested.

The objective of this study was to examine the role slash size (both length and diameter), cutting date, and sunlight intensity play in pine engraver colonization and development in ponderosa pine slash. Specifically, we tested three hypotheses relevant to slash management strategies for minimizing pine engraver increase. First, (1) reducing log size will cause reductions in pine engraver colonization, and brood production, (2) slash generated during July through November will have lower pine engraver colonization, brood production, and overall population growth than slash created other times of the year and (3) increasing sunlight intensity will cause reductions in pine engraver colonization, brood production, and overall population growth. Results are discussed in relation to slash management guidelines in the Southwest.

2. Materials and methods

2.1. Study area

The study was located within Camp Navajo Army Depot, 16 km west of Flagstaff, AZ; T22N, R5E, Sections 31 and 32. The study site was approximately 300 ha, in ponderosa pine/gambel oak (*Quercus gambelii* Nutt.) stands of varying densities. Stands used in this study varied from open (5 m²/ha) to closed canopy (28 m²/ha BA) and had elevated pine engraver populations due to a recent outbreak and ongoing slash production. The study was conducted over 2 years (October 2004–September 2006).

2.2. Experimental design and slash treatments

A completely randomized block design was used with cutting date, sunlight intensity, and log size as factors. A 50 m grid was overlaid on forested stands for determining where groups of logs would be located. To test for effects of log size, logs were cut into four lengths (15, 30, 45, and 60 cm), in each of four diameter classes (10, 15, 20, and 25 cm) for a total of 16 treatment combinations. At each grid point, logs were cut from one to three trees in order to create all 16 log sizes. Groups of 16 log sizes ($n = 15$) were placed on the ground at the base of a small (1–1.5 m high, by 1–2 m wide) slash pile, consisting of the crown of the felled tree(s). The direction of the logs in relation to the pile was assigned randomly. This was repeated until 15 piles (i.e. groups of 16 treatment combinations and slash) had been created for each of three stand densities. In order to test the cutting date hypothesis, the above procedure was repeated in four cutting periods per year in each of 2 years. Logs were cut in fall (15–29 October 2004 and 25–31 October 2005), winter (20–31 January 2005 and 3–11 January 2006), spring (18–29 April 2005 and 4–19 April 2006), and summer (20–28 July 2005 and 10–13 July 2006).

2.3. Environmental variables

Environmental factors of sunlight and precipitation were recorded. Sunlight intensity classes of low, partial or high were assigned to groups of logs. Sunlight intensity classes were created by utilizing stand densities of 28, 14, or 5 (± 4) m^2/ha of basal area (BA), representing low, partial, or high sunlight levels, respectively, and sunlight intensity class (hereafter referred to as sunlight level) for each point was determined using a variable radius plot (10 basal area factor prism, ft^2/ac). To control for potential confounding effects of slope and aspect, points that fell on a slope of greater than 10% were omitted. Stand density was a surrogate measure for sunlight intensity; therefore light intensity was also measured using a photosynthetically active radiation (PAR) ceptometer (Decagon Devices, Inc., 950 NE Nelson Court, Pullman, WA 99163, USA). Precipitation was expected to affect condition of slash, especially phloem moisture. Monthly data were obtained from National Weather Service Forecast Center, Belmont, AZ.

2.4. Beetle response variables

The response variable emergence-hole (i.e. the hole created by offspring beetles when exiting logs) was measured in the field by observing the exterior of bark, on a 15 cm wide strip (circumference) at the center of each log. Emergence-holes were measured on the fall, winter, and spring-cut logs 7–18 July 2005 and on the summer-cut logs 7–13 April 2006. In Year 2, we measured emergence-holes on the fall, winter, and spring-cut logs 18 July through 2 August 2006, and on summer-cut logs 9–13 October 2006. We also measured beetle attacks (indicated by piles of frass created by a bark beetle burrowing into bark) on the Year 2 fall, winter, and spring-cut logs 19–25 May 2006. Summer-cut logs in Year 2 had not yet been cut at the time attacks were measured, therefore, attack data were not obtained for these logs.

2.5. Statistical analysis

The effects of cutting date, sunlight level, and their interaction on attack and emergence-hole density were analyzed with two-way analysis of variance (ANOVA), using piles (i.e. groups of 16 treatment combinations averaged) as an experimental unit. Year 1 (2004–2005) emergence-hole data were transformed with the reciprocal ($1/x$) and Year 2 (2005–2006) emergence-hole data were transformed by the square root to meet ANOVA assumptions of normality and homogeneity of variance. To analyze the effect of log length on beetle attack and emergence density, within each pile (i.e. block) data from logs with the same length were averaged over the various diameters. These data were then analyzed as a one factor randomized block using ANOVA. The same procedure (averaging and ANOVA analysis) was used in the analysis of the effect of diameter on beetle attack and emergence data. Analysis of effects of length and diameter on emergence density was done for each year separately. All analysis of variance calculations were conducted using SigmaStat version 3.1 statistical software (SPSS Inc., 2004).

A measure of population growth rate, growth rate index (GRI), was also calculated for the three cutting periods in which we had attack and emergence density data (Year 2 fall, winter, and spring). Pine engravers have been estimated to maintain an average sex ratio of three females per male (Schmitz, 1972); therefore our estimate of parent generation density was calculated as attack density times four, with each attack hole representing one male and three female beetles. Estimates of offspring generation density were calculated as emergence-hole density times 1.2 (Sartwell, 1971). GRI was then calculated as estimated emergence density/estimated attack density. An average GRI was then calculated for each pile and, using this pile average, the effects of cutting date and

light levels were tested using two-way ANOVA. Pairwise comparisons for all significant effects found in all ANOVA analyses were calculated using Tukey Test.

3. Results

3.1. Environmental variables

Sunlight intensity was significantly different between the three stand densities ($F_{2,27} = 46.6, P < 0.001$), matching our expectations of increasing stand density, as measured by basal area of live trees, reducing sunlight intensity within a stand [low stand density/high light, mean = 1617.3 ± 29.3 (S.E.) $\mu\text{mol m}^{-2} \text{s}^{-1}$; medium stand density/partial light, mean = 1165.5 ± 70.8 (S.E.) $\mu\text{mol m}^{-2} \text{s}^{-1}$; high stand density/low light, mean = 857.8 ± 59.3 (S.E.) $\mu\text{mol m}^{-2} \text{s}^{-1}$]. Precipitation levels also differed between the 2 study years (Fig. 1). Precipitation in the first year was close to double that of the second year, with annual precipitation of 78.5 cm (30.9 in.) and 41.0 cm (16.4 in.) in Year 1 and Year 2, respectively. In Year 1, winter precipitation was heavy, with 47.4 cm (18.7 in.) of precipitation falling during the November to March time period, while 9.9 cm (3.90 in.) fell in the same time period in Year 2 [30-year average; 28 cm (11.05 in.), Staudenmaier et al., 2007]. Monsoon precipitation (i.e. summer rainy season), measured as June through August precipitation, was 15.6 cm (6.16 in.) in Year 1 and 23.6 cm (9.3 in.) in Year 2 compared to the 30-year average of 14.5 cm (5.72 in.). Also, the official monsoon starting date was 18 July in Year 1 (second latest on record) and 28 June in Year 2 (National Weather Service Forecast Center, Tucson, AZ).

3.2. Beetle colonization

Beetle attack density (in fall, winter, and spring cuttings of Year 2, dry winter) was significantly affected by cutting date (Fig. 2A, $F_{2,126} = 13.5, P < 0.001$), sunlight level ($F_{2,126} = 16.3, P < 0.001$), and the interaction of cutting date and sunlight level (Fig. 2B, $F_{4,126} = 5.2, P < 0.001$). Fall-cut logs had lower attack densities (Tukey: $P < 0.05$) than both winter and spring-cut logs (Fig. 2A). A negative relationship between sunlight level and attack density was seen in logs cut in winter and spring, but not in fall-cut logs (Fig. 2B). Both log length ($F_{3,402} = 149.0, P < 0.001$) and diameter ($F_{3,402} = 31.4, P < 0.001$) had significant effects on attack density (Fig. 3A and B). Twenty centimeter diameter logs had the highest attack density (Tukey: $P < 0.05$); their attack density, 3.4 attacks per 1,000 cm^2 , was significantly higher than all other log diameters (Fig. 3A). Fifteen centimeter length logs had the lowest attack densities and significant increases (Tukey: $P < 0.05$) in attack

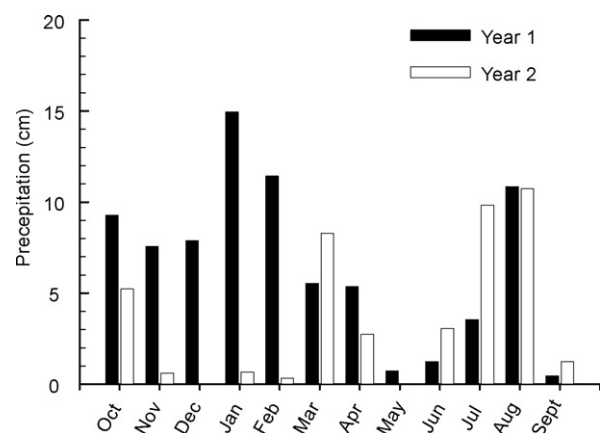


Fig. 1. Monthly precipitation recorded at Belmont, AZ, National Weather Service Forecast Center (approximately 6.5 km east of study site).

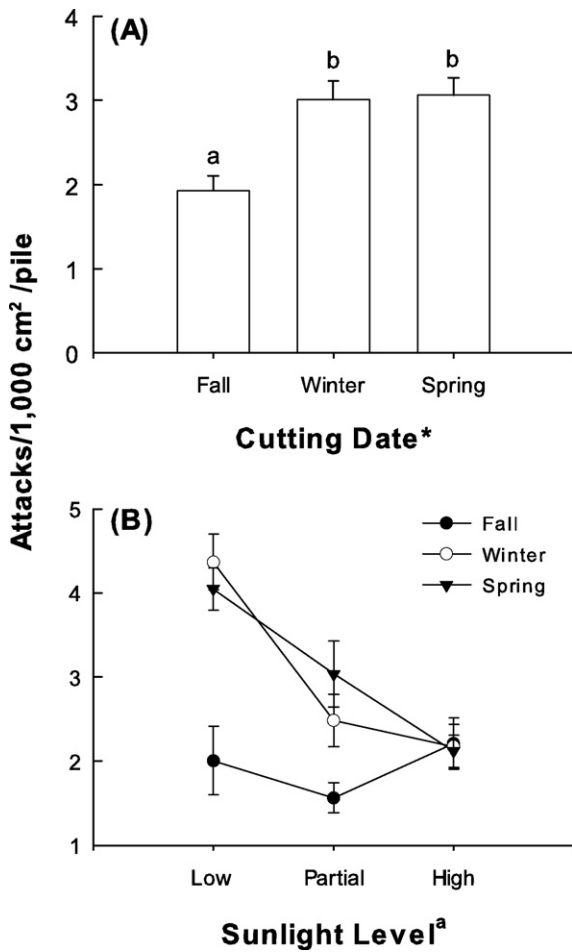


Fig. 2. Comparison of effects of (A) cutting date and (B) sunlight level on *I. pini* attack density on ponderosa pine logs cut in fall 2005, and winter and spring 2006 in Northern Arizona. Bars and points represent mean \pm S.E. Bars with different letters are significantly different at the 0.05 level using Tukey Test. ^aStatistically significant difference at the 0.05 alpha level using two-way ANOVA. ^bStatistically significant interaction between cutting date and sunlight level at the 0.05 alpha level using two-way ANOVA.

density were found with each increase in log length, with the exception of 60 cm length logs (Fig. 3B).

3.3. Brood development

Evidence of successful brood production (emergence-holes) was found across all sunlight levels and cutting periods in both years. There were, however, significant differences in emergence density caused by cutting date (Year 1, $F_{3,168} = 4.9$, $P < 0.01$; Year 2, $F_{3,168} = 13.2$, $P < 0.001$), and the interaction of cutting date and sunlight level (Year 1, $F_{6,168} = 2.4$, $P = 0.03$; Year 2, $F_{6,168} = 2.9$, $P = 0.01$). Sunlight intensity alone did not have a significant effect on emergence densities either year (Year 1, $F_{2,168} = 0.5$, $P = 0.61$; Year 2, $F_{2,168} = 0.4$, $P = 0.68$). In both years, the lowest emergence density was found in the spring-cut logs (Fig. 4). In Year 1, the highest emergence densities were in the fall and winter-cut logs, but, in Year 2, the highest emergence densities were in the summer-cut logs (Fig. 4). In Year 1 (wet winter), beetle emergence decreased with increasing light intensity in logs cut in the spring and summer, but the reverse occurred for fall and winter-cut logs when emergence density increased with increasing light intensity (Fig. 5A). In Year 2 (dry winter), however, all cutting periods experienced reduced emergence density when light intensity increased, with the exception of summer-cut logs (Fig. 5B).

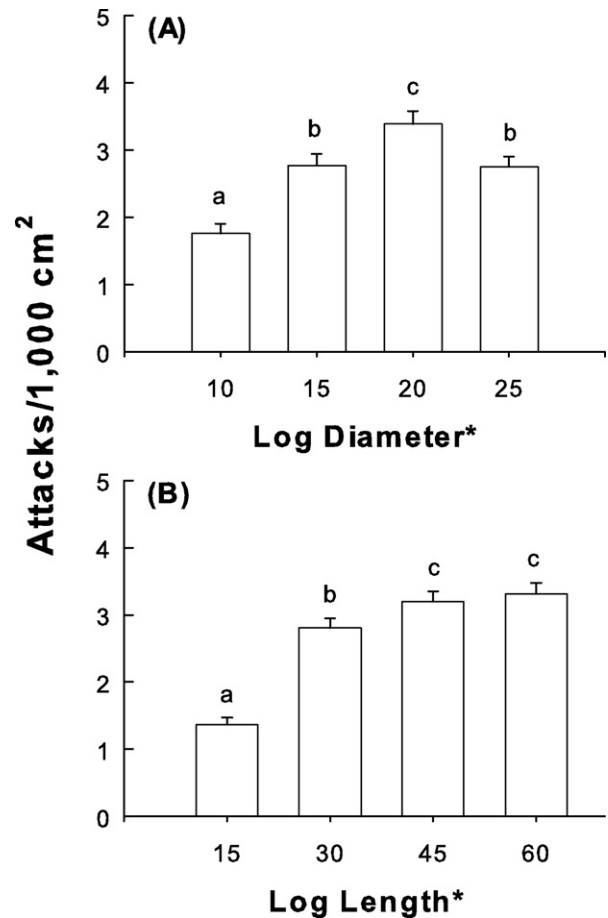


Fig. 3. Comparison of effects of log (A) diameter and (B) length on *I. pini* attack density on ponderosa pine logs cut in fall 2005, and winter and spring 2006 in Northern Arizona. Bars represent mean \pm S.E. Bars with different letters are significantly different at the 0.05 level using Tukey Test. ^aStatistically significant difference at the 0.05 alpha level using two-way ANOVA.

Log diameter had a significant effect on emergence density in both years (Year 1, $F_{3,510} = 50.4$, $P < 0.001$; Year 2, $F_{3,522} = 25.9$, $P < 0.001$). In Year 1, 10 and 15 cm diameter logs had the highest emergence densities; 20 cm logs were lower than both 10 and 15 cm logs, and 25 cm logs were lower than all other sizes (Tukey: $P < 0.05$) (Fig. 6A). In Year 2, 15 and 20 cm diameter logs did not differ and had higher emergence densities than both the 10 and 25 cm logs (Fig. 6B).

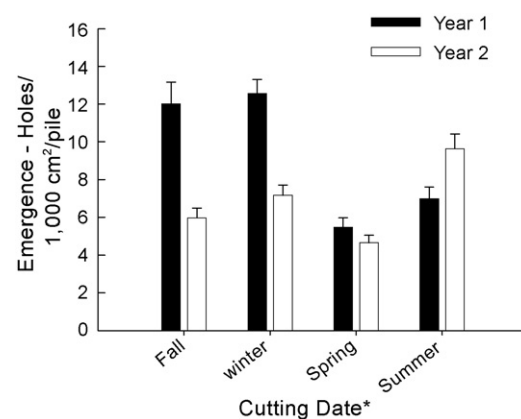


Fig. 4. Comparison of *I. pini* emergence-hole density by all cutting periods in both study years for ponderosa pine slash produced in Northern Arizona. Bars represent mean for cutting period \pm S.E. ^aStatistically significant difference at the 0.05 alpha level using two-way ANOVA.

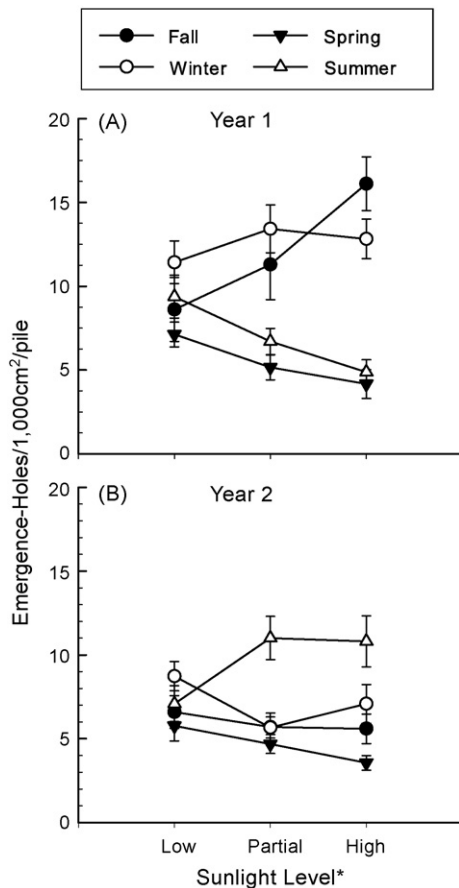


Fig. 5. Comparisons of the effects of sunlight level on *I. pini* emergence-hole density for ponderosa pine logs cut in each cutting cohort of (A) Year 1 and (B) Year 2. Points represent mean \pm S.E. *Statistically significant interaction of cutting date and sunlight level at the 0.05 alpha level using two-way ANOVA.

Log length also had a significant effect on emergence densities in both years (Year 1, $F_{3,510} = 184.9$, $P < 0.001$; Year 2, $F_{3,522} = 242.4$, $P < 0.001$), having a positive relationship in both years (Fig. 6C and D). In both years, cutting logs into 15 cm lengths precluded beetle reproduction, with the exception of logs cut in summer.

3.4. Beetle population growth (GRI)

There was a significant effect (in the first three cutting periods of Year 2) on GRI caused by cutting date ($F_{2,126} = 11.3$, $P < 0.001$; Fig. 7A), and the interaction of cutting date and sunlight level ($F_{4,126} = 2.4$, $P = 0.05$; Fig. 7B). Sunlight level alone had no significant effect on GRI ($F_{2,126} = 0.2$, $P = 0.79$), however. Beetles that attacked logs cut in fall had positive population growth, while beetles that attacked logs cut in winter and spring had negative growth (Fig. 7A, >1 represents an increase in beetle numbers). Fall-cut logs, placed in low and partial sunlight, had population growth, while fall-cut logs placed in high sunlight had negative growth. Winter and spring-cut logs had negative population growth in all but the winter-cut/high sunlight logs (Fig. 7B). In order to determine the influence of intraspecific competition on GRI, we ran a Pearson's correlation coefficient on estimated attack density and GRI, and found a highly significant negative correlation ($n = 135$, $P < 0.001$, $r = -0.49$).

4. Discussion

We found strong evidence that sunlight levels affect pine engraver attack behavior, but were unable to conclude that high

sunlight levels have consistent negative effects on phloem condition or beetle reproduction. Fewer beetles attacked logs in high sunlight compared with logs in partial and low sunlight levels. This is in agreement with the findings of Villa-Castillo and Wagner (1996), who in a study conducted from May to August in Northern Arizona, found fewer pine engraver beetle attacks in logs exposed to high sunlight intensity compared with logs exposed to low to moderate sunlight. Changes in sunlight levels associated with thinned forests affect microclimate and may affect beetle behavior through increases in wind speed and temperature in open stands (Amman et al., 1988; Bartos and Amman, 1989; Schmitz et al., 1989; Bartos and Booth, 1994). Differences in microclimate may influence beetle behavior directly (Bartos and Amman, 1989) or indirectly through the influence of warmer temperatures on the dispersion and activity of aggregation pheromones (Fares et al., 1980; Schmitz et al., 1989). In our study, beetle attacks on logs exposed to high sunlight levels were concentrated on the bottom aspect, while logs in partial and low sunlight levels had attacks on the top and bottom aspects (CJH, personal observation), suggesting that differences in microclimate may be having direct impacts on beetle attack behavior.

Pine engraver reproduction was not impacted by sunlight levels alone, but we did find a significant effect caused by the interaction of sunlight level and cutting date. Villa-Castillo and Wagner (1996) suggested that adverse microclimate conditions generated in logs (12 cm diameter) exposed to high sunlight levels likely reduce brood production. In our study, the interaction of sunlight levels and cutting date was most likely due to the interactions of sunlight (stand density) and weather patterns (e.g. winter precipitation). We speculate that in years with high winter and spring precipitation, beetles may have more reproductive success in logs exposed to high sunlight levels that aids in evaporation of excess phloem moisture prior to beetle flight. Alternately, logs containing excess moisture levels may also have more bark beetle pathogens, such as fungi, viruses, etc., that could result in decreased brood production in the low and medium intensity light. In dry winters, however, logs exposed to high sunlight levels may experience reduction in phloem quality due to higher temperatures and increased desiccation rates. Climatic conditions could also allow for prolonged retention of phloem moisture, and increases in phloem temperature associated with high sunlight levels could increase development rates, thereby benefiting beetle reproductive success.

To better test the effect sunlight level and subsequent phloem temperature regimes have on beetle reproductive success, attack density would need to be held constant to avoid any potential confounding effects. Larval success has been linked to intraspecific competition (Aukema and Raffa, 2002). In our case, beetles in logs with low attack densities likely benefited as indicated by negative correlation between attack density and GRI. The highest beetle population growth rates occurred in logs that also experienced the lowest attack densities (low and mid sunlight level logs cut in the fall of Year 2), suggesting that high larval survival rates are dependent on low attack densities. The question remains, however, as to whether log conditions (e.g. phloem temperature and phloem moisture) are more ideal for rapid beetle reproduction in high or low sunlight conditions. Higher sunlight levels, and consequent increased temperature, could cause a potential tradeoff between increased development rates and decreased phloem quality caused by more rapid desiccation.

Very short logs had poor beetle reproduction, which was most likely caused by rapid phloem desiccation. Steed and Wagner (2004) found no effect due to log length on attack, egg, or emergence density but suggested phloem in close proximity to cut ends of logs may dry rapidly, and that by cutting slash into short pieces brood production in slash could be reduced. Our results

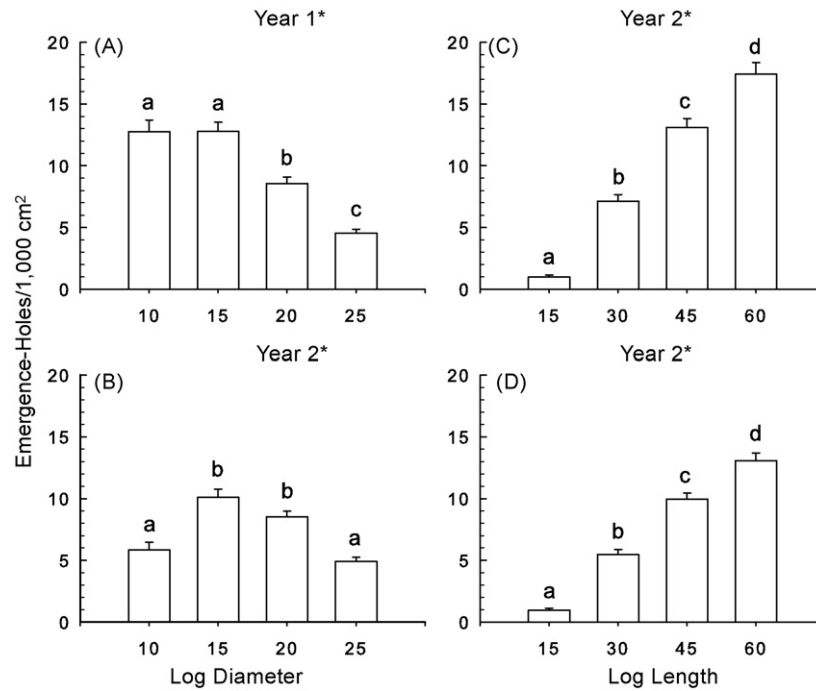


Fig. 6. Comparison of the effects of log diameter in (A) Year 1 and (B) Year 2 and log length in (C) Year 1 and (D) Year 2 on *I. pini* emergence density in ponderosa pine logs cut in Northern Arizona. Bars represent mean \pm S.E. *Statistically significant difference at the 0.05 alpha level using ANOVA analysis.

provide evidence to support this hypothesis. By looking at lengths ≤ 60 cm, we found lengths (≤ 30 cm) where rapid desiccation apparently becomes an important factor.

Bark thickness may also be an important factor in oviposition preference (Struble and Hall, 1955), and has been proposed as the main factor in the niche segregation of some sympatric species (Amezaga and Rodriguez, 1998). Additional energy expenditure required for boring through thick bark may also cause a preference for attacking areas with thin bark in some beetle species (Kolb et al., 2006). Because ponderosa pine bark thickness increases with increasing tree diameter (10 cm diameter \approx 6 mm thickness; 23 cm diameter \approx 12 mm) (Kolb et al., 2006), we considered diameter as a surrogate for bark thickness. Wesley (1995) found pine engraver and *I. lecontei* preferred 10 cm diameter logs over 5 or 20 cm, and Steed and Wagner (2004) found pine engraver beetles had a preference for larger diameter logs in logs 5–20 cm in diameter. Struble and Hall (1955) state that *I. paraconfusus* Lanier in California has preference for and produces the largest broods in slash that has bark thickness between 6.4 and 12.7 cm, and that bark thicker than 25.4 cm is seldom attacked. Our results suggest that pine engraver will readily attack log diameters between 10 and 25 cm but attack preference seems to peak between 15 and 20 cm.

Thin bark of small diameter logs or tree species has been indicated as a cause of rapid desiccation (Amman, 1969; Schenk and Benjamin, 1969; Cole, 1978; Six et al., 2002). Steed and Wagner (2004) hypothesized that smaller diameter logs constitute habitat that is more vulnerable to degradation, which in years of strongly unfavorable environmental conditions, can have a negative effect on reproduction. Our study provides some evidence for this idea. In a year with little winter precipitation (Year 2), small diameter logs (10 cm) had low emergence densities relative to the other diameters that year, as opposed to in a year with a wet winter (Year 1) in which logs with diameters less than 15 cm had the highest emergence density. This suggests that phloem conditions may have declined considerably in Year 2 due to moisture loss prior to beetle emergence. We suspect that factors such as

humidity, cloud cover, air movement, temperature, and precipitation are all important factors in phloem desiccation that, under the right conditions, have the ability to limit the effect that thin bark may have on phloem desiccation.

Cutting date did not have the negative impact on beetle reproduction that we hypothesized. In Year 1, fall-cut logs had the highest emergence density, and in Year 2 beetles attacking fall-cut logs experienced population growth. Studies conducted in both laboratory and field settings have confirmed that phloem moisture decreases with time after cutting (Villa-Castillo and Wagner, 1996; Gara et al., 1999; Redmer et al., 2001). Phloem desiccation rates may not be fast enough to preclude beetle development, however. In a study conducted in eastern Oregon, Sartwell (1970) found successful pine engraver attacks on ponderosa pine logs cut in each month of the year. The author concluded that, similar to our study, his findings did not explain why pine engraver is more likely to kill residual trees following February–July thinning treatments than after August–January treatments. Solving this discrepancy is hampered by the paucity of studies that test the effect of cutting date on beetle reproduction and studies correlating differences in brood production due to cutting date with actual tree mortality. Villa-Castillo and Wagner (1996) hypothesized that degraded phloem quality leads to reduced pheromone production in attacking males and a subsequent reduction in attack density. Our study provides some evidence of slash degradation affecting attack behavior with fall-cut logs in Year 2, a drier than average winter, having lower attack densities than logs cut in winter or spring of that year.

It should also be noted that there are a number of confounding factors that may have affected our results. Although every attempt was made to identify only attack and emergence holes created by pine engraver, and emergence traps confirmed that pine engraver was the dominant species utilizing slash in this area, there are many other species (e.g. *I. lecontei*, *I. latidens*, *Pityogenes carinulatus*, or *Orthotomicus latidens*) that potentially could have colonized these logs and been mistaken for pine engraver beetles. In addition, air holes created by beetles, most likely created to mitigate fungal

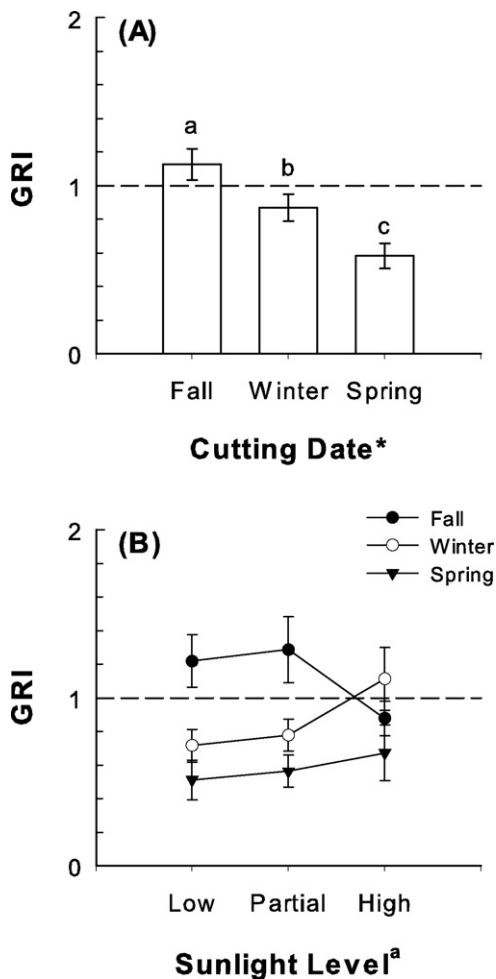


Fig. 7. Comparisons of the effect of (A) cutting date and (B) sunlight levels for each cutting date cohort on *I. pini* population growth (GRI) for each of the fall, winter, and spring cutting periods of 2005–2006. A GRI value of one represents no change in population. ^aStatistically significant difference at the 0.05 alpha level when analyzed two-way ANOVA. ^aStatistically significant interaction of cutting date and sunlight level at the 0.05 alpha level when analyzed with two-way ANOVA.

growth (Melnikova, 1964), may have been counted as emergence holes. Furthermore, the effect of bark thickness on number of beetles emerging per emergence hole is not known. Despite these confounding factors we feel that, because of the sample sizes utilized in this study, our statistical tests and interpretations were robust.

4.1. Management implications

Based on the results of our study, treatments to affect slash size should work to minimize *Ips* population growth. Beetle performance was reduced in logs shorter than 30 cm. Although cutting slash to 15–30 cm lengths would be time and labor expensive, this option may be appropriate in high value settings and sensitive areas. Chipping slash may be a less expensive option for larger management areas, but creates a source of strong but ephemeral bark beetle attractant when slash is chipped (Fettig et al., 2006).

Slash management guidelines to minimize *Ips* impacts associated with logging and thinning suggest late summer/fall cutting to allow for phloem desiccation and subsequent reduced bark beetle reproduction; increased beetle mortality caused by inter-specific competition and winter cold temperature; and reduced beetle flight activity during late fall (Craighead, 1927; Livingston,

1979; Parker, 1991; Gara et al., 1999; Fettig et al., 2006). In addition, Parker (1991) suggests that residual live trees may be less susceptible during mid to late summer. Our results show that neither fall (October) cutting nor high sunlight levels consistently reduced emergence densities or beetle population growth rates.

Presence of slash when beetles are emerging in the spring is an important factor in slash management with respect to mortality of residual trees. Attacks on live trees have been attributed to beetles reared in spring and early summer, and outbreaks have been associated with abundant slash and drought weakened trees (Struble and Hall, 1955; Parker, 1991). High levels of reproductive success in the first generation would lead to high flight densities in late spring and potential attacks on live trees. This would be of concern in Arizona because late spring is often a time of drought stress. Successful tree defense is highly dependent on tree condition and initial resin flow rate is a function of physiological vigor (Berryman et al., 1989). Sufficient drought stress occurring in late spring may allow for successful beetle colonization and subsequent tree death; however, ponderosa pine in Northern Arizona may retain strong tree defenses at this time (Gaylord, 2004). Despite adaptations and defenses ponderosa pine display, and because of the physiological stresses they frequently experience in late spring, it would be prudent to avoid any activities (e.g. providing slash in the early spring) that have the potential to cause beetle populations increases at this time.

Slash management guidelines that propose that there is a safe cutting window that lasts through December (Livingston, 1979; Parker, 1991; Gara et al., 1999) may be presenting a risky proposition when they assert that this material will dry out and become unfavorable habitat for spring emerging beetles. Gara et al. (1999) found a doubling of the subsequent beetle population in beetles attacking logs created in December, and our results show that logs cut as early as October can remain suitable beetle habitat until the following spring.

In Arizona, climate varies widely across the elevation range of ponderosa pine (Gaylord et al., 2008; Williams et al., 2008), and can be a critical factor in determining the desiccation rate of slash. Mean annual precipitation increases at higher elevations due to orographic processes (Sheppard et al., 2002), while mean temperature decreases with higher elevation (Williams et al., 2008). Because of differences along this climatic gradient, slash scattered in low elevation stands should dry more rapidly than slash scattered in high elevation ponderosa pine stands. At lower elevations, managers could thin stands in the fall with greater confidence that scattered slash would dry sufficiently prior to spring beetle flights; and piled slash could possibly be burned the winter following cutting. At high elevation sites, however, managers should not rely solely on desiccation of fall cut slash as an *Ips* management strategy due to the greater presence of snow.

Based on the results of this study showing differences in brood production by several of the treatments, slash management guidelines for ponderosa pine in the US Southwest may need to be revised. Further work is needed to determine the relationship between increased brood production (GRI) in slash and subsequent tree mortality across seasonal, elevational, and site quality gradients. Increased brood production in slash at high elevation/high quality sites may not pose as great of risk as increased brood production at low elevation/low site quality sites where host trees may be more stressed and there are more generations per year of beetles (Williams et al., 2008).

Acknowledgements

We thank the Arizona Army National Guard for funding of this research on Camp Navajo. We are grateful to the following people who assisted during various phases of the project: Kenneth

Baumgartner, Vernon Bunker, T. Seth Davis, Beverly Loomis, Mayra Moreno, Eric Osborne, Laine Smith, Juliana Suby, Kelly Williams, and Wesley Winslow. This research was supported in part by Arizona Department of Emergency and Military Affairs Interagency Service Agreement, Bark Beetle and Slash Management Project Camp Navajo, Bellemont, AZ, DEMA Contract No. M4-0094.

References

- Amezaga, I., Rodriguez, M.A., 1998. Resource partitioning of four sympatric bark beetles depending on swarm dates and tree species. *For. Ecol. Manage.* 109, 125–127.
- Amman, G.D., 1969. Mountain pine beetle emergence in relation to depth of lodgepole pine bark. USDA For. Serv. Intermountain Res. Note INT-69. Ogden, UT.
- Amman, G.D., McGregor, M.D., Schmitz, R.F., Oakes, R.D., 1988. Susceptibility of lodgepole pine to infestation of mountain pine beetles following partial cutting of stands. *Can. J. For. Res.* 18, 688–695.
- Anderson, R.F., 1948. Host selection by the pine engraver. *J. Econ. Entomol.* 41, 596–602.
- Aukema, R.H., Raffa, K.F., 2002. Relative effects of exophytic predation, endophytic predation, and intraspecific competition on a subcortical herbivore: consequences to the reproduction of *Ips pini* and *Thanasimus dubius*. *Oecologia* 133, 483–491.
- Bartos, D.L., Amman, G.D., 1989. Microclimate: an alternative to tree vigor for a basis for mountain pine beetle infestation. USDA For. Serv. Res. Pap. INT-400.
- Bartos, D.L., Booth, G.D., 1994. Effects of thinning on temperature dynamics and mountain pine beetle activity in a lodgepole pine stand. USDA For. Serv. Res. Pap. INT-RP-479.
- Berryman, A.A., Raffa, K.F., Millstein, J.A., Stenseth, N.C., 1989. Interaction dynamics of bark beetle aggregation and conifer defense rates. *Oikos* 56, 256–263.
- Buckhorn, W.J., 1957. Scheduling of cutting or thinning operations in immature stands of ponderosa pine to minimize damage by the Oregon pine *Ips*. USDA For. Serv. Pac. NW For. Range Expt. Sta. 2.
- Cole, W.E., 1978. Management strategies for preventing mountain pine beetles epidemic in lodgepole pine stands: based on empirical models. In: Kibbee, D.L., Berryman, A.A., Amman, G.D., Stark, R.W. (Eds.), *Proceeding, Symposium: Theory and Practice of Mountain Pine Beetle Management in Lodgepole Pine Forests*, Washington State University, Pullman, WA, April 25–27. Forest, Wildlife, and Range Experiment Station, University of Idaho, Moscow, pp. 87–97.
- Covington, W.W., Moore, M.M., 1994. Changes in multiresource conditions in ponderosa pine forests since Euro-American settlement. *J. For.* 92, 39–47.
- Craighead, F.C., 1927. The Relation of Insects to Slash Disposal. Circular 411. U.S. Department of Agriculture, Forest Service, p. 12.
- DeGomez, T.E., Young, D.J., 2002. Pine Bark Beetles. University of Arizona College of Agriculture and Life Sciences Publication AZ 1300, Tucson, AZ.
- DeGomez, T.E., Fettig, C.J., McMillin, J.D., Anhold, J.A., Hayes, C., 2008. Managing slash to minimize colonization of residual leave trees by *Ips* and other bark beetle species following thinning in southwestern ponderosa pine. *Univ. of Arizona Coll. Agr. Life Sci. Bull.*, 1449.
- Fares, Y., Sharpe, P.J.H., Magnuson, C.E., 1980. Pheromone dispersion in forests. *J. Theor. Biol.* 81, 335–359.
- Fellin, D.G., 1980. A review of some interactions between harvesting, residue management, fire and insects and diseases. In: *Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests: Symposium Proceedings*, U.S. Department of Agriculture, Forest Service, GTR-INT-90, pp. 335–414.
- Fettig, C.J., McMillin, J.D., Anhold, J.A., Hamud, S.M., Borys, R.R., Dabney, C.P., Seybold, S.J., 2006. The effects of mechanical fuel reduction treatments on the activity of bark beetles (Coleoptera: Scolytidae) infesting ponderosa pine. *For. Ecol. Manage.* 230, 55–68.
- Fettig, C.J., Klepzig, K.D., Billings, R.F., Munson, A.S., Nebeker, T.E., Negrón, J.F., Nowak, J.T., 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. *For. Ecol. Manage.* 238, 24–53.
- Furniss, R.L., Carolin, V.M., 1977. Western forest insects. U.S. For. Serv. Misc. Publ. 1339.
- Gara, R.I., Millegan, D.R., Gibson, K.E., 1999. Integrated pest management of *Ips pini* (Coleoptera: Scolytidae) populations in south-eastern Montana. *J. Appl. Ent.* 123, 529–534.
- Gaylord, M.L., 2004. Bark beetle and tree physiology seasonal patterns in Northern Arizona. Masters Thesis. Northern Arizona University, Flagstaff, AZ, 109 pp.
- Gaylord, M.L., Williams, K.K., Hofstetter, R.W., McMillin, J.D., DeGomez, T.E., Wagner, M.R., 2008. Flight temperature thresholds for southwestern ponderosa pine bark beetles. *Environ. Entomol.* 37, 57–69.
- Haack, R.A., Foltz, J.L., Wilkinson, R.C., 1984. Longevity and fecundity of *Ips calligraphus* (Coleoptera: Scolytidae) in relation to slash pine phloem thickness. *Ann. Entomol. Soc. Am.* 77, 657–662.
- Haack, R.A., Wilkinson, R.C., Foltz, J.L., Cornell, J.A., 1987. Spatial attack pattern, reproduction, and brood development of *Ips calligraphus* (Coleoptera: Scolytidae) in relation to slash pine phloem thickness: a field study. *Environ. Entomol.* 16, 428–436.
- Hindmarch, T.D., Reid, M.L., 2001. Forest thinning affects reproduction in pine engravers (Coleoptera: Scolytidae) breeding in felled lodgepole pine trees. *Environ. Entomol.* 30, 919–924.
- Kegley, S.J., Livingston, R.L., Gibson, K.E., 1997. Pine engraver, *Ips pini* (Say), in the United States. USDA For. Serv. FIDL Leaflet 122.
- Kennedy, P.C., 1969. Causes of the 1966 *Ips pini* outbreak. *Mich. Acad.* 2, 87–92.
- Kolb, T.E., Guerard, N., Hofstetter, R.W., Wagner, M.R., 2006. Attack preference of *Ips pini* on *Pinus ponderosa* in Northern Arizona: tree size and bole position. *Agric. For. Entomol.* 8, 295–303.
- Livingston, R.L., 1979. The pine engraver *Ips pini* (Say) in Idaho, life history, habits, and management recommendation. Idaho Department of Lands Report 79-3.
- Massey, C.L., Parker, D.L., 1981. Arizona five-spined *Ips*. U.S. Department of Agriculture, Forest Service, Forest Insect and Disease Leaflet 116.
- Melnikova, N.I., 1964. Biological significance of the air holes in egg tunnels of *Scolytus ratzeburgi* Jans. (Coleoptera: Ipsidae). *Entomol. Rev.* 43, 16–23.
- National Fire Plan, 2000. What is the national fire plan? <http://www.fireplan.gov/overview/whatis.html>.
- Parker, D.L., 1991. Integrated Pest Management Guide: Arizona Five-spined *Ips*, *Ips lecontei* Swaine, and Pine Engraver, *Ips pini* (Say), in Ponderosa Pine. U.S. Department of Agriculture, Forest Service, Southw. Region, R-3 91-9, Albuquerque, NM.
- Redmer, J.S., Wallin, K.F., Raffa, K.F., 2001. Effect of host tree seasonal phenology on substrate suitability for the pine engraver (Coleoptera: Scolytidae): implications for population dynamics and enemy free space. *J. Econ. Entomol.* 94, 844–849.
- Sartwell, C., 1970. *Ips pini* attack density in ponderosa pine thinning slash as related to felling date in eastern Oregon. U.S. Department of Agriculture, For. Serv. Res. Pap. PNW 131.
- Sartwell, C.S., 1971. *Ips pini* (Coleoptera: Scolytidae) emergence per exit hole in ponderosa pine thinning slash. *Ann. Entomol. Soc. Am.* 64, 1473–1474.
- Schenk, J.A., Benjamin, D.M., 1969. Note on the biology of *Ips pini* in central Wisconsin jack pine forests. *Ann. Entomol. Soc. Am.* 62, 480–485.
- Schmitz, R.F., 1972. Behavior of *Ips pini* during mating, oviposition, and larval development. *Can. Entomol.* 104, 1723–1728.
- Schmitz, R.F., McGregor, M.D., Amman, G.D., Oakes, R.D., 1989. Effect of partial cutting treatments of lodgepole pine stands on the abundance and behaviour of flying mountain pine beetles. *Can. J. For. Res.* 19, 566–574.
- Sheppard, P.R., Comrie, A.C., Packin, G.D., Angersbach, K., Hughes, M.K., 2002. The climate of the US Southwest. *Clim. Res.* 21, 219–238.
- Six, D.L., Vander Meer, M., DeLuca, T.H., Kolb, P., 2002. Pine engraver (*Ips pini*) colonization of logging residues created using alternative slash management systems in Western Montana. *West. J. Appl. Forestry* 17, 96–100.
- SPSS, Inc., 2004. SigmaStat Statistical Software Version 3.1. Chicago, IL.
- Staudenmaier Jr., M., Preston, R., Sorenson, P., 2007. Climate of Flagstaff, Arizona. NOAA Technical Memorandum NWS WR-273.
- Steed, B.E., Wagner, M.R., 2004. Importance of log size on host selection in reproductive success of *Ips pini* (Coleoptera: Scolytidae) in ponderosa pine slash of Northern Arizona and western Montana. *J. Econ. Entomol.* 97, 436–450.
- Struble, G.R., Hall, R.C., 1955. The California Five-spined Engraver: Its Biology and Control. Circular 964. U.S. Department of Agriculture, Forest Service, p. 21.
- Villa-Castillo, J., Wagner, M.R., 1996. Effect of overstory density of *Ips pini* (Coleoptera: Scolytidae) performance in ponderosa pine slash. *J. Econ. Entomol.* 86, 1537–1545.
- Wesley, V.S., 1995. Effects of log diameter, length, and aspect on *Ips* brood production in ponderosa pine slash. M.S. Thesis. Northern Arizona University, Flagstaff.
- Wilkinson, R.C., Foltz, J.L., 1982. *Ips* engraver beetles: identification, biology, and control. In: *Ga. For. Res. Paper*, vol. 35.
- Williams, K.K., McMillin, J.D., DeGomez, T.E., Clancy, K.M., Miller, A., 2008. Influence of elevation on bark beetle (Coleoptera: Curculionidae Scolytinae) community structure and flight periodicity in ponderosa pine forests of Arizona. *Environ. Entomol.* 37, 94–109.