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ABSTRACT

Carbaryl is regarded among the most effective, economically viable, and ecologically-compatible insecticides available for protecting conifers from bark beetle attack in the western United States. Treatments are typically applied in spring prior to initiation of bark beetle flight for that year. We evaluated the efficacy of spring and fall applications for protecting individual lodgepole pine, *Pinus contorta* Dougl. ex Loud, from mortality attributed to mountain pine beetle, *Dendroctonus ponderosae* Hopkins, the most notable forest insect pest in western North America. Both spring and fall treatments of 2.0% a.i. carbaryl (Sevin® SL) were efficacious for two field seasons, while results from a third field season were inconclusive due to insufficient beetle pressure. We discuss the implications of these and other results to the management of *D. ponderosae*.

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1. Introduction

Mountain pine beetle, *Dendroctonus ponderosae* Hopkins, is a major disturbance in forests of western North America where it colonizes at least 15 tree species, most notably lodgepole pine, *Pinus contorta* Dougl. ex Loud (Negrón and Fettig, 2014). The geographic distribution of *D. ponderosae* ranges from British Columbia, Canada; east to South Dakota, United States; and south to Baja California, Mexico (Wood, 1982). Populations have recently been reported in Nebraska, United States (Costello and Schaupp, 2011), and the insect is expanding its range northward in British Columbia and eastward in Alberta, Canada (De la Giroday et al., 2012). In the last decade, outbreaks of *D. ponderosae* have been severe, long-lasting, and well-documented with >27 million hectares of forest impacted (USDA Forest Service, 2012; British Columbia Ministry of Forests, Lands and Natural Resource Operations, 2013). Millions of *P. contorta* have been killed annually. While *D. ponderosae* is an important ecological component of these forests, extensive levels of tree mortality resulting from outbreaks may have undesirable social impacts; for example negatively affecting aesthetics, recreation, fire risk and severity, human safety, timber production, and real estate values. About 6.7% of forests in the United States are classified at high risk [defined as >25% of stand density represented by trees >2.54 cm dbh (diameter at breast height, 1.37 m above ground level) will die in the next 15 years] to insect and disease outbreaks, and *D. ponderosae* is ranked among the most damaging of all mortality agents considered (Krist et al., 2014).

Fettig et al. (2014a) defined two general approaches for reducing the negative impacts of *D. ponderosae* on forests. Indirect control is designed to reduce the probability and severity of future infestations within treated areas by manipulating stand, forest and/or landscape conditions. Direct control involves short-term tactics designed to address current infestations by manipulating beetle populations, and includes, among other strategies, applications of liquid formulations of contact insecticides to the bole of individual trees using ground-based sprayers at high pressure (e.g., ≥2241 kPa). Only high-value, individual trees growing in unique environments (e.g., in residential, recreational or administrative sites) or under unique circumstances are treated. Tree mortality in these environments generally results in undesirable impacts such as reduced shade, screening, aesthetics, property values and visitor use. Dead trees also pose potential risks to public safety, requiring routine inspection and eventual removal. Trees growing in progeny tests, seed orchards, or those genetically resistant to certain forest diseases may also be considered for treatment, especially if

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outbreak populations of *D. ponderosae* are present. During large-scale outbreaks, hundreds of thousands of trees may be treated annually in the western United States (Fettig et al., 2013), however once an outbreak subsides preventive treatments are often no longer necessary. In recent years, systemic insecticides injected directly into the tree bole have also been demonstrated effective (Fettig et al., 2014b), and registered for use as a preventive treatment. Insecticides are no longer used for direct or remedial control of *D. ponderosae* (i.e., subsequent treatment of infested trees or logs to kill developing and/or emerging brood).

Insecticides are typically applied to all bole surfaces to a height of ~10.6–15.2 m until runoff during spring prior to initiation of *D. ponderosae* flight that year. Carbaryl is regarded among the most effective, economically viable, and ecologically-compatible insecticides available for protecting individual trees from bark beetle attack in the western United States (Fettig et al., 2006a,b, 2013), but other active ingredients (a.i.) (e.g., bifenthrin and permethrin, among others) are available and effective. Application efficiency, the percentage of carbaryl applied that is retained on trees, ranges from ~80 to 90% (Fettig et al., 2008). Carbaryl is an acetylcholinesterase inhibitor that prevents cholinesterase enzymes from breaking down acetylcholine, increasing both the level and duration of action of the neurotransmitter acetylcholine, which leads to rapid twitching, paralysis and ultimately death (Hastings et al., 2001). Carbaryl is considered essentially nontoxic to birds, moderately toxic to mammals, fish and amphibians, and highly toxic to honey bees, *Apis mellifera* L., and several aquatic insects (Jones et al., 2003). An application of 2.0% a.i. carbaryl in spring is commonly used to protect individual *P. contorta* and typically reapplied every other year during outbreaks. The objective of this study was to determine the efficacy of spring and fall applications of 2.0% a.i. carbaryl for protecting individual *P. contorta* from mortality attributed to *D. ponderosae*. It would be highly desirable if fall treatments (i.e., applied ~9 months prior to beetle flight) yielded similar efficacy to spring treatments (i.e., applied several weeks prior to beetle flight) thereby expanding the treatment window while potentially reducing several negative environmental impacts.

2. Materials and methods

This study was conducted on the Bridger-Teton National Forest, Wyoming (43° 08′ 37.8″ N, 110° 52′ 47.4″ W; 1903 m elevation) during 2010–2014. Site selection was based on aerial and ground surveys indicating that *D. ponderosae* was colonizing and killing trees in the area. Surrounding stands had a mean live tree (≥12.9 cm dbh) density of 20.7 m^2 of basal area/ha of which 98.4% was *P. contorta* with a mean dbh of 26.0 cm. The remainder was represented by Engelmann spruce, *Picea engelmannii* Parry ex Engelm., and subalpine fir, *Abies lasiocarpa* (Hooker) Nuttall. About 12.2% of *P. contorta* and 16.3% of *P. contorta* basal area had been killed by *D. ponderosae* during the previous two years within the study area, which represent conditions that warrant the use of insecticides to protect high-value trees. For example, several campgrounds in the area were treated with carbaryl to reduce tree losses attributed to *D. ponderosae* (Blackford, 2013).

Thirty (30) trees were confirmed uninfested and randomly assigned to each of five treatments ($N = 150$): (1) 2.0% a.i. carbaryl (Sevin® SL; Bayer Environmental Science, Montvale, NJ 07645; EPA Reg. No. 432-1227) in water (pH = 6.5) applied 21–22 June 2011 ("Spring" treatment), (2) 2.0% a.i. carbaryl (Sevin® SL) in water (pH = 6.4) applied 15–16 September 2010 ("Fall" treatment), and (3–5) untreated controls used to assess *D. ponderosae* "pressure" (based on mortality of untreated, baited trees) during 2011–2013. Experimental trees were separated by >100 m. There was a significant difference in *P. contorta* dbh among treatments ($F_{4,145} = 3.4$, $P = 0.01$), but presumably exerted little influence as experimental trees in all treatments averaged >23 cm dbh (Table 1), the preferred size class for *D. ponderosae* colonization (Björklund and Lindgren, 1999). Insecticides were applied with a trailer-mounted hydraulic sprayer (Model 0021-F200-1511 with P15 pump; GNC Industries, Inc., Pocahontas, AR) powered by an 11-hp gasoline motor at 2241 kPa, using a Mighty Mag Tree Spray Gun (Product No. 11-854-00; GNC Industries Inc.) with 0.319-cm diameter nozzle aperture, which allowed treatment of the entire bole until runoff to a height of ~12 m. All insecticides were applied between 0630 and 1600 when wind speeds were <11 km/h.

One commercially-available two-component tree bait [*trans*-verbenol (~1.2 mg/d) and *exo*-brevicomin (~0.3 mg/d); Contech Inc., Delta, BC] was stapled to the bole of each *P. contorta* at ~2 m in height on the northern aspect prior to the initiation of *D. ponderosae* flight each year. The manufacturer estimates the life expectancy of these baits is 100–150 days depending on weather conditions, covering most of the flight activity period (~15 June to 1 October). All baits were removed after *D. ponderosae* flight ceased. Tree mortality was estimated initially based on external characteristics of the condition, distribution and density of *D. ponderosae* attacks on tree boles (none, unsuccessful attack, strip attack, and mass attack based on pitch tubes and boring dust) in the fall of each year. However, mortality was based on presence (dead) or absence (live) of crown fade, an irreversible symptom of tree mortality, in June the following year (e.g., in 2012 for trees colonized in 2011). All surviving trees in each treatment (if <7 were killed), and the appropriate control was baited the following year.

The only criterion used to determine the effectiveness of each treatment was whether individual trees died due to colonization by *D. ponderosae*. Treatments were considered to have sufficient beetle pressure if ≥60% of the untreated control trees were killed as a result of *D. ponderosae* attack. Insecticide treatments were considered efficacious when <7 trees die as a result of *D. ponderosae* attack (Hall et al., 1982; Shea et al., 1984). These criteria were established based on a sample size of 22–35 trees and test of the null hypothesis, Ho: S (survival ≥90%). These parameters provide a conservative binomial test ($\alpha = 0.05$) to reject Ho when more than six trees die. The power of this test, that is the probability of having made the correct decision in rejecting Ho, is 0.84 (Hall et al., 1982; Shea et al., 1984). This experimental design is accepted as the standard for evaluating insecticides for tree protection in the western United States, and provides a very conservative test of efficacy (Fettig et al., 2013).

Table 1
Efficacy of an alternative timing of ground-based applications of carbaryl to protect individual *Pinus contorta* from mortality attributed to *Dendroctonus ponderosae*, Bridger-Teton National Forest, Wyoming (43° 08′ 37.8″ N, 110° 52′ 47.4″ W; 1903 m elevation), 2010–2014.

Treatment	Mean dbh ± SEM[a]	2011 Mortality[b]/n	2012 Mortality[b]/n	2013 Mortality[b]/n
Spring	31.2 ± 1.2 ab	0/30	0/29[c]	1/29[c]
Fall	31.8 ± 1.1 ab	0/30	0/30	4/30
Untreated control 2011	32.0 ± 0.8 a	27/30	–	–
Untreated control 2012	31.8 ± 1.1 ab	–	26/30	–
Untreated control 2013	27.3 ± 1.0 b	–	–	16/30

[a] Means ± SEM followed by the same letter are not significantly different ($P > 0.05$). Dbh, diameter at breast height, 1.37 m above ground level.
[b] Based on the presence (dead) or absence (live) of crown fade the following June.
[c] One tree was windthrown and therefore excluded from the experiment.

3. Results

In 2011 and 2012, *D. ponderosae* pressure was sufficient to adequately challenge treatments as 90% and 87% of untreated controls died from colonization by *D. ponderosae*, respectively. Both spring and fall treatments of 2.0% Sevin® SL provide adequated levels of tree protection for both field seasons (Table 1). Unfortunately, *D. ponderosae* pressure was insufficient to adequately challenge treatments in 2013 as only 53% of the untreated, baited controls died (Table 1).

4. Discussion

In previous studies, several rates and formulations of carbaryl have been evaluated for protecting individual *P. contorta* from mortality attributed to *D. ponderosae* (reviewed by Fettig et al., 2013). Most indicate that two field seasons of protection can be expected with a single application when properly applied prior to *D. ponderosae* flight in late spring or early summer. For example, Shea and McGregor (1987) evaluated the efficacy of 0.5%, 1.0% and 2.0% Sevimol® and Sevin® XLR and found all concentrations and formulations were effective for protecting *P. contorta* for one year. The 1.0% and 2.0% rates were effective for two years. Today, carbaryl (e.g., Sevin® SL and Sevin® XLR Plus, among others) is commonly used to protect individual *P. contorta* from *D. ponderosae* attack in the western United States. Failures in efficacy occasionally occur and are typically associated with inadequate coverage, improper (e.g., using an alkaline water source with pH >8), or inaccurate mixing resulting in solutions of reduced concentration, improper storage, and/or improper timing (e.g., applying treatments to trees already successfully attacked by *D. ponderosae*) (Fettig et al., 2013). Our study agrees with others demonstrating the efficacy of spring applications of 2.0% Sevin® SL for protecting individual *P. contorta* from mortality attributed to *D. ponderosae* for two field seasons (Table 1).

In this study, we determined that carbaryl treatments applied in fall provided two field seasons of tree protection as well (Table 1). This was unexpected as fall treatments were subjected to an additional nine months of degradation compared to spring treatments (i.e., from mid-September 2009 to mid-June 2010) before being challenged by *D. ponderosae*, which we thought would be sufficient to limit efficacy to one field season. While the amount of carbaryl on pine bark necessary to impart tree protection from *D. ponderosae* is unknown, Fettig et al. (2011) found no significant differences in the survival probability of *D. ponderosae* in filter paper assays between 20,000 $\mu g\ g^{-1}$ carbaryl (i.e., 2% a.i.) and lesser concentrations until reaching 20 $\mu g\ g^{-1}$ (i.e., via 10-fold serial dilutions). In topical assays, significantly higher survival probabilities were observed for concentrations $\leq$2000 $\mu g\ g^{-1}$ of carbaryl, suggesting levels below 2000 $\mu g\ g^{-1}$ may be less effective for tree protection. Mean LC_{50} values for *D. ponderosae* were 132.9 $\mu g\ g^{-1}$ at 12 h (Fettig et al., 2011). Page et al. (1985) reported residues collected from *P. contorta* bark sprayed with carbaryl in Colorado were 890 $\mu g\ g^{-1}$, and declined to 531 $\mu g\ g^{-1}$ 16 months later, but were still sufficient to impart tree protection at 16 months. In a similar study, Peterson and Costello (2013) reported 1308 $\mu g\ g^{-1}$ were detected one day after treatment and 1465 $\mu g\ g^{-1}$ 12 months after treatment. The authors attributed the increase to refinement of their sampling technique. Residues and residual activity are largely influenced by abiotic conditions (Fettig et al., 2013), which affect microbial activity and thus degradation of carbaryl. Increased longevity is expected in cooler environments, such as those typified by *P. contorta*. For example, 2.0% a.i. carbaryl protects white spruce, *Picea glauca* (Moench) Voss, and Lutz spruce, *P. glauca* X *lutzii* Little, from colonization by spruce beetle, *Dendroctonus rufipennis* Kirby, for three field seasons in south-central Alaska (Werner et al., 1986).

Our finding that fall treatments yield two field seasons of efficacy is desirable for several reasons: (1) Treatments require transporting sprayers and other large equipment into remote areas, which is often problematic in spring when snow drifts and poor road conditions limit access. (2) Many sites where carbaryl treatments are commonly applied (e.g., campgrounds) occur near intermittent or ephemeral streams associated with runoff from snowmelt limiting applications in spring due to label restrictions concerning the use of no-spray buffers to protect non-target aquatic organisms (Fettig et al., 2008). Trees within no-spray buffers are left untreated and therefore vulnerable to colonization by *D. ponderosae*. By delaying treatments to fall, fewer no-spray buffers would likely be necessary. (3) Recent declines in bumble bee populations, *Bombus* spp. (Hymenoptera: Bombidae), important pollinators in high-elevation forests in the western United States, have been reported and primarily attributed to habitat loss and declines in floral abundance and diversity (Goulson et al., 2008). *Bombus* spp. forage over large distances (>2000 m) and flowering resources are required throughout the flight period, which generally ceases in late summer and early fall. As such, delaying carbaryl treatments until fall after the majority of their flight activity period may reduce any negative impacts associated with carbaryl treatments. To that end, applications of carbaryl on trees have been challenged on the basis of the toxicity of residues to *A. mellifera*, however *Bombus* spp. are reported to be much less susceptible to carbaryl residues than *A. mellifera* (Mommaerts and Smagghe, 2011). (4) During large-scale outbreaks of *D. ponderosae* or other bark beetles, limitations in the availability of labor and equipment to implement carbaryl treatments are common, especially during spring due to competition with agricultural producers. As such, procuring contracts in fall may be less difficult and costly than in spring. (5) Fall treatments are less likely to interfere with forest recreation as, for example, many campgrounds are already closed for the season by this time of year.

Studies on the effectiveness of insecticides to protect *P. contorta* from mortality attributed to *D. ponderosae* have generally been limited to two field seasons due primarily to the costs and labor involved or early failures in efficacy (Fettig et al., 2013). We attempted to determine efficacy for a third field season, but were unable to do so due to insufficient mortality in the untreated, baited controls in 2013 (Table 1). If two additional control trees had died, *D. ponderosae* pressure would have been sufficient to make definitive estimates of efficacy (Hall et al., 1982; Shea et al., 1984), and we would have concluded that both spring and fall treatments were effective for three field seasons. However, we caution the reader that higher levels of tree mortality should be expected in both carbaryl treatments as well as the untreated, baited control in the third and subsequent years.

Future research should examine the efficacy of fall treatments in other hosts impacted by *D. ponderosae* where carbaryl treatments are commonly used, such as ponderosa pine, *P. ponderosa* Dougl. ex Laws. We hope that forest health professionals and other resource managers use this publication and other reports to make informed, judicious decisions concerning the appropriate use of insecticides to protect *P. contorta* from mortality due to *D. ponderosae*.

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This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides in the United States must be registered by appropriate State and/or Federal agencies before they can be recommended.

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