Effectiveness of Two Systemic Insecticides for Protecting Western Conifers from Mortality Due to Bark Beetle Attack

Donald M. Grosman, Christopher J. Fettig, Carl L. Jorgensen, and A. Steven Munson

ABSTRACT

Bark beetles (Coleoptera: Curculionidae, Scolytinae) are important tree mortality agents in western coniferous forests. Protection of individual trees from bark beetle attack has historically involved applications of liquid formulations of contact insecticides to the tree bole using hydraulic sprayers. More recently, researchers looking for more portable and environmentally safe alternatives have examined the effectiveness of injecting small quantities of systemic insecticides directly into trees. In this study, we evaluated trunk injections of experimental formulations of emamectin benzoate and fipronil for preventing tree mortality due to attack by western pine beetle (*Dendroctonus brevicomis* LeConte) on ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) in California, mountain pine beetle (*Dendroctonus ponderosae* Hopkins) on lodgepole pine (*Pinus contorta* Dougl. ex Loud.) in Idaho, and spruce beetle (*D. rufipennis* [Kirby]) on Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) in Utah. Fipronil appeared ineffective for protecting *P. ponderosa* from mortality due to *D. brevicomis* over the 3 years in California because of insufficient mortality of untreated, baited control trees the first 2 years and high mortality of the fipronil-treated trees in the third year. Emamectin benzoate was effective in providing protection of *P. ponderosa* from *D. brevicomis* during the third year following a single application. To our knowledge, this is the first demonstration of the successful application of a systemic insecticide for protecting individual conifers from mortality due to bark beetle attack in the western United States. Estimates of efficacy could not be made during both field seasons in *P. contorta* because of insufficient mortality in control trees. Both emamectin benzoate and fipronil were ineffective for protecting *P. engelmannii* from *D. rufipennis*. Lower ambient and soil temperatures and soil moisture may have limited chemical movement and thus efficacy at the Idaho and Utah sites.

Keywords: *Dendroctonus brevicomis*, *Dendroctonus ponderosae*, *Dendroctonus rufipennis*, systemic insecticides, single-tree protection

Bark beetles (Coleoptera: Curculionidae, Scolytinae) are responsible for extensive conifer mortality throughout western North America. In particular, the last decade has seen extremely high levels of bark beetle-caused tree mortality in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests of Arizona, California, Colorado, and South Dakota; lodgepole pine (*Pinus contorta* Dougl. ex Loud.) forests of western Canada and the Rocky Mountains; and spruce (*Picea* spp.) forests of south-central Alaska and the Rocky Mountains (US Forest Service 2009). Local and regional outbreaks of the western pine beetle (*Dendroctonus brevicomis* LeConte), mountain pine beetle (*Dendroctonus ponderosae* Hopkins), and spruce beetle (*Dendroctonus rufipennis* [Kirby]) cause extensive amounts of tree mortality on a near annual basis. Bark beetle attacks cause top kill, tree mortality, and subsequent replacement by other tree species, and they may affect timber and fiber production, wildfire severity, water quality and quantity, fish and wildlife populations, recreation, grazing capacity, real estate values, biodiversity, carbon storage, endangered species, and cultural resources (Coulson and Stephen 2006).

Trees located in residential, recreational (e.g., campgrounds), or administrative sites can be more susceptible to bark beetle attack as a result of stress associated with soil compaction, drought, mechanical injury, or vandalism (Haverty et al. 1998). Tree losses in these environments generally result in undesirable effects, such as reduced shade, screening, esthetics, and increased fire risk. Dead trees pose potential hazards to public safety, requiring routine inspection and maintenance (Johnson 1981). Furthermore, property values may be significantly reduced by mortality of adjacent shade and ornamental trees (McGregor and Cole 1985). As the wildland-urban interface continues to expand, more high-valued residential trees are placed at risk to bark beetle attack. In addition, some conifer species (Engelmann spruce [*Pinus engelmannii*, Parry ex Engelm.] and

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; gram (g): 1 g = 0.035 oz; liter (L): 1 L = 61.02 $in.^2$, = 0.908 quart (dry), = 1.057 quart (liquid).

whitebark pine [*Pinus albicaulis* Engelm.]) are experiencing extensive mortality due to *D. rufipennis* and *D. ponderosae*, respectively, in remote, high-elevation stands (Logan and Powell 2001; A.S. Munson, personal observation). The current abundance of trees and forests susceptible to bark beetle infestations and outbreaks (Krist et al. 2007) underlines the need to develop new methods for protecting individual trees against bark beetle attack.

Protection of individual trees has historically involved applications of insecticides to the tree bole using hydraulic sprayers. Several products have been registered with the U.S. Environmental Protection Agency (EPA) for this use but are now canceled or withdrawn, including benzene hexachloride (Lindane), fenitrothion (Pestroy), and chlorpyrifos (Dursban). Fettig et al. (2006a) reported that carbaryl is still one of the most effective, economically viable, and ecologically compatible insecticides available for protecting individual trees from bark beetle attack in forest and urban landscapes of the western United States. However, its use on trees recently has been challenged during EPA reregistration (EPA 2007). Pyrethroids, such as permethrin (Astro) and bifenthrin (Onyx), are registered for use in recreational areas and can be effective (Shea et al. 1984, DeGomez et al. 2006, Fettig et al. 2006a, 2006b), but they typically provide protection for only one field season, compared with two field seasons for carbaryl. In general, spray applications often require large equipment (e.g., trucks and trailers), which can be problematic. Furthermore, concerns regarding the potential for insecticide spray to drift onto adjacent bodies of water are common, although recent evidence suggests drift poses little threat if appropriate no-spray buffers are used (Fettig et al. 2008).

Previous research indicates that several systemic insecticides, such as acephate (Orthene) (Crisp et al. 1979, unpublished data, in Billings 1980), fenitrothion (Pestroy), dicrotophos (Bidrin) (Dalusky et al. 1990), and azadirachtin (neem) (Duthie-Holt and Borden 1999), are ineffective for preventing tree mortality due to bark beetle attack. Oxydemeton methyl (Metasystox-R) applied by Mauget injectors (Inject-a-cide) is registered for protecting individual trees from attack by several western bark beetle species, but it has been shown to be largely ineffective (Haverty et al. 1996) and is not recommended for use. Previous lack of treatment efficacy may be due to the type of insecticide material (nontoxic to target pest), tree physiology complications (resin flow prevents uptake or inability of chemical to move into/through phloem tissue), or environmental influences (water stress, temperature). More recently, Grosman and Upton (2006) evaluated the effectiveness of dinotefuran, emamectin benzoate (Denim), fipronil, and imidacloprid (IMA-jet) for preventing *Ips* spp. attacks and brood development on standing, stressed trees and bolt sections of loblolly pine (*Pinus taeda* L.) in East Texas. Both emamectin benzoate and fipronil significantly reduced *Ips* spp. colonization success and levels of mortality in stressed trees. Imidacloprid and dinotefuran were ineffective. DeGomez et al. (2006) also reported that implants of dinotefuran were ineffective for preventing *Ips* spp. attacks on *P. ponderosa* in Arizona. Additional studies in Mississippi and Alabama have shown that emamectin benzoate and fipronil are capable of significantly reducing *P. taeda* mortality due to southern pine beetle (*Dendroctonus frontalis* Zimmermann) attack for a period of 2 years after injection (Grosman et al. 2009). Given the above results, we hypothesized that injections of emamectin benzoate and fipronil may be useful tools for protecting western conifers from mortality due to bark beetle attack. The objectives of this study were to assess the effectiveness and duration of emamectin benzoate and fipronil for protecting *P. ponderosa* from *D. brevicomis* attack in California, *P. contorta* from *D. ponderosae* attack in Idaho, and Engelmann spruce (*P. engelmannii* Parry ex Engelm.) from *D. rufipennis* attack in Utah.

Methods

This study was conducted at three locations: (1) Calaveras County, California (38.24°N, 120.24°W; 1,230-m elevation with a species composition of 65% *P. ponderosa*); (2) Salmon-Challis National Forest, Idaho (44.21°N, 115.86°W; 2,061-m elevation with 97% *P. contorta*); and (3) Manti-LaSal National Forest, Utah (39.69°N, 111.23°W, 2,892-m elevation with 63% *P. engelmannii*). At each site, 30 (*P. ponderosa* in California and *P. contorta* in Idaho) or 35 (*P. engelmannii* in Utah) randomly selected trees were assigned to each of three or four treatments: (1) trunk injections of an experimental formulation of emamectin benzoate (4% active ingredient [a.i.], Syngenta Crop Protection, Inc., Greensboro, NC) mixed 1:1 with methanol (histological, $>$99% pure, Fisher Scientific, Pittsburg, PA); (2) trunk injections of an experimental formulation of fipronil (300 g [a.i.] per liter emulsifiable concentrate, BASF Corp., Research Triangle Park, NC) mixed 1:5:14 with methanol and distilled water; (3) bole sprays of 0.06% a.i. bifenthrin (Onyx, FMC Corporation, Philadelphia, PA; California only) or 2.0% a.i. carbaryl (Sevin SL, Bayer Environmental Science, Montvale, NJ; Idaho only); and (4) two (Idaho and Utah) or three (California) groups of untreated, baited controls. Bole sprays were included in California and Idaho as commercial standards because the effectiveness of these insecticides has been well documented (e.g., Fettig et al. 2006a). Bole sprays were not applied in Utah because of lack of access for spray equipment. One group of untreated, baited controls (i.e., host trees) was used to assess bark beetle pressure during each field season (2005–2007 depending on study location).

Emamectin benzoate and fipronil were directly injected into the tree bole at four cardinal points 0.3 m above the ground using the Tree IV microinfusion system (Arborjet, Inc., Woburn, MA). Insecticides were applied at 0.2 or 0.4 g a.i. per 2.54-cm diameter to trees $<$25 or $\geq$25 cm dbh (1.37 m aboveground level), respectively, in mid- to late May (California and Idaho) or late August (Utah) 2005. Insecticide-treated trees were allowed 6 (Idaho), 7 (California), or 32 (Utah) weeks to translocate insecticides before being challenged by baiting with commercial lures for each respective bark beetle species. Bifenthrin and carbaryl bole treatments were applied with a hydraulic sprayer until runoff to a height of about 12 m. All bole sprays were applied when wind speeds were $<$11 km/hour. Our tree injection technique represents a closed system and therefore could be applied without regard to wind conditions. Application and evaluation dates are listed in Tables 1–4.

Study sites were selected on the basis of reported activity of beetle infestations in the area within 1 year prior to treatment. Test trees were spaced at least 100 m apart to increase the likelihood that sufficient numbers of beetles would be in the vicinity of each test tree to rigorously challenge these treatments. All treated trees and the first set of untreated controls (California and Idaho) were baited with appropriate species-specific lures (Contech, Inc., Delta, British Columbia; Tables 2–4) for 2–14 weeks, depending on beetle pressure in each area. Baits were removed from all trees at a site when significant numbers of attacks ($>$50/m^2) occurred on the untreated, baited controls. In Utah, baits were deployed in April, well before *D. rufipennis* flight occurs. Surviving trees in each treatment (if fewer

Table 1. Site characteristics and experimental conditions associated with systemic insecticide injection trials in California, Idaho, and Utah, 2005–2007.

Site	Coordinates	Elevation (m)	Tree species	Mean (range) dbh (cm)	Injection dates	Air temperature at injection (°C)	Mean (range) uptake time: Emamectin benzoate	Mean (range) uptake time: Fipronil
							. . . .(min)	. . . .
California	38.24°N, 120.24°W	1,230	*P. ponderosae*	38.6 (29.2–56.9)	May 16–18, 2005	5–26	22 (9–41)	23 (11–50)
Idaho	44.21°N, 115.86°W	2,061	*P. contorta*	25.4 (20.1–47.0)	May 31 to June 2, 2005	2–16	26 (5–45)	28 (11–68)
Utah	39.69°N, 111.23°W	2,892	*P. engelmannii*	40.1 (23.6–61.5)	Aug. 29–31, 2005	−1 to 24	29 (14–70)	27 (20–63)

Table 2. Effectiveness of single applications of emamectin benzoate, fipronil, and bifenthrin for protecting *P. ponderosa* from mortality attributed to *D. brevicomis* attack, Calaveras County, California, 2005–2007.

Treatment	Mortality/n 2005[a]	2006[b]	2007[c]	Cumulative
Emamectin benzoate	0/30	1/30	0/29	1/30
Fipronil	5/29[d]	2/23[d]	6/21	13/28
Bifenthrin	0/30	1/30	8/29	9/30
Untreated control	13/30	12/30	21/35	46/95

[a] Trees were baited starting July 5, 2005, with racemic frontalin (3 mg/24 hours), racemic exobrevicomin (3 mg/24 hours), and myrcene (18 mg/24 hours) for 41 days. Mortality, based on crown fade, was assessed on June 6–7, 2006.

[b] Trees were baited starting June 6, 2006, for 76 days. Mortality was assessed on June 26, 2007.

[c] Trees were baited starting June 26, 2007, for 85 days. Mortality was assessed on July 20, 2008.

[d] One tree was removed from sample because of lost bait in 2005, and one was accidentally harvested in 2006.

Table 3. Effectiveness of single applications of emamectin benzoate, fipronil, and carbaryl for protecting *P. contorta* from mortality attributed to *D. ponderosae* attack, Custer County, Idaho 2005–2006.

Treatment	Mortality/n 2005[a]	2006[b]	Cumulative
Emamectin benzoate	8/30	5/22	13/30
Fipronil	11/30	0/19	11/30
Carbaryl	0/30	3/30	3/30
Untreated control	11/30	14/29[c]	25/59

[a] Trees were baited starting July 13, 2005, with transverbenol (1.2 mg/24 hours) and exobrevicomin (0.3 mg/24 hours) for 14 days. Mortality, based on crown fade, was assessed on Sept. 19, 2006.

[b] Trees were baited starting July 31, 2006, for 14 days. Mortality was assessed on Aug. 30, 2007.

[c] One tree was lost because of evidence of prior beetle attack in 2005.

Table 4. Effectiveness of single applications of emamectin benzoate and fipronil for protecting *P. engelmannii* from mortality attributed to *D. rufipennis* attack, Emery and Carbon counties, Utah, 2006.

Treatment	Mortality/n in 2006[a]
Emamectin benzoate	33/35
Fipronil	34/34[b]
Untreated control	33/33[b]

[a] Trees were baited starting April 10, 2006, with racemic frontalin (2–3 mg/24 hours) and α-pinene (75–150 mg/24 hours) for 100 days. Mortality, based on crown fade, was assessed on Aug. 28–29, 2007.

[b] Three trees were lost because of harvesting.

than seven were killed) and subsequent sets of untreated controls were baited each year.

Insecticide treatments (emamectin benzoate, fipronil, and bole sprays) were evaluated for their ability to prevent tree mortality due to bark beetle attack. Therefore, methodology to evaluate treatment efficacy required that two criteria be met to demonstrate effective tree protection: (1) trees had to be challenged by bark beetles, and (2) trees did not die from bark beetle attack during the course of the study (Shea et al. 1984, Haverty et al. 1998, Strom et al. 2004). Trees were considered dead when foliage began to "fade" to yellow and red, an irreversible symptom of tree mortality. Treatments were considered to have sufficient beetle pressure if ≥60% of the untreated, baited control trees died from bark beetle attack. Insecticide treatments were considered efficacious when fewer than seven baited trees died from bark beetle attack (Shea et al. 1984). These criteria were established on the basis of a sample size of 22–35 trees/treatment and the 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 has been used previously for determining the efficacy of bole sprays in the western United States (e.g., Shea et al. 1984, Haverty et al. 1985, 1998, Fettig et al. 2006a, 2006b) and provides a very conservative test.

Results and Discussion

During this study, we observed no external symptoms of phytotoxicity associated with any treatment. Uptake time (i.e., the amount of time required for trunk injected solutions to completely enter the tree) for both emamectin benzoate and fipronil ranged from 5 to 70 minutes (Table 1). Injections conducted at lower elevations and higher ambient temperatures (California) appeared to take less time than those applied at higher elevations and lower temperatures (Idaho and Utah). Other authors have made similar observations. For example, Schultz et al. (2009) reported that average uptake time was 15 to 60 minutes in Sitka spruce (*Picea sitchensis* [Bong.] Carr.) in Alaska, whereas it was about 8 minutes per tree in *P. ponderosa* in California, and attributed much of the difference to climatic conditions.

California: *D. brevicomis* and *P. ponderosa*

In 2005 and 2006, beetle pressure was insufficient to validate the effectiveness of treatments as only 43 and 40% of untreated, baited controls died from *D. brevicomis* attack, respectively (Table 2). During this time only one tree (3%) faded because of bark beetle attacks in each of the emamectin benzoate and bifenthrin treatments, whereas 25% (7 trees) died in the fipronil treatment. In 2007, 60% mortality was observed in the untreated, baited control, permitting us to make definitive conclusions regarding efficacy (Shea et al. 1984). In this study, a single application of emamectin benzoate was effective for protecting individual *P. ponderosa* from *D. brevicomis* attack during the third year after treatment, but fipronil was ineffective. Only one emamectin benzoate-treated tree died during the course of this study, despite trees being repeatedly attacked on an annual basis.

Bifenthrin applied as a bole spray failed to protect trees during the third summer after treatment (Table 2). Prior studies have suggested that pyrethroids, including permethrin (Shea et al. 1984), permethrin plus-C (Fettig et al. 2006b), cyfluthrin and esfenvalerate (Haverty et al. 1998), and bifenthrin (Fettig et al. 2006a), provide a minimum of one field season of protection with a single application. Three field seasons of efficacy had been considered unlikely, but prior studies have generally been concluded after two field seasons. For example, Fettig et al. (2006a) demonstrated that Onyx applied at 0.06 and 0.12% a.i. was effective in protecting *P. ponderosa* against *D. brevicomis* for two field seasons in California, but the study was discontinued after the second field season. This study confirms that 0.06% a.i. Onyx (i.e., the maximum registered rate) is only effective for protecting *P. ponderosa* from *D. brevicomis* attack for two field seasons in California (Table 2).

Idaho: *D. ponderosae* and *P. contorta*

In 2005 and 2006, beetle pressure was insufficient to adequately challenge the treatments, as only 37 and 52% of untreated, baited controls died from bark beetle attack, respectively (Table 3). An assessment of experimental trees 2 weeks after initial baiting in 2005 indicated that more than 90% of control trees were "heavily" attacked, based on the presence of oxidized phloem material in pitch tubes and/or points of attack containing phloem boring dust and/or dry frass. On the basis of these signs, it was predicted that a sufficient number of these trees would die from bark beetle attack to test efficacy (Haverty et al. 1998), and therefore baits were removed. Unfortunately, mortality of control trees did not reach the 60% threshold necessary to make conclusions regarding efficacy (Shea et al. 1984) at the time of the evaluation. About 27% (8 trees) and 37% (11 trees) mortality was observed in the emamectin benzoate and fipronil treatments, respectively, during the first field season after treatment. These values exceed the critical threshold for efficacy despite insufficient levels of control tree mortality (Table 3). No fipronil-treated trees died during the second field season following injection, compared with 52% mortality of the controls. Only three carbaryl-treated trees died during the course of this study (Table 3), which agrees with results from prior studies using similar sample sizes (e.g., Fettig et al. 2006a).

Utah: *D. rufipennis* and *P. engelmannii*

In 2006, beetle pressure was sufficient to adequately challenge these treatments, as 100% of untreated, baited controls died from *D. rufipennis* attack (Table 4). Emamectin benzoate and fipronil were ineffective, as 94% (33 trees) and 100% (34 trees, 1 tree lost to harvest) of the injected trees, respectively, were killed during the first field season (Table 4).

Management Implications

Currently, tactics for managing bark beetle infestations in the western United States are limited to prevention by silvicultural practices (i.e., thinning to reduce stand density and presumably host susceptibility; Fettig et al. 2007), applications of semiochemicals for some bark beetle-host complexes (e.g.,verbenone for *D. ponderosae* and MCH for *D. rufipennis*) to protect individual trees or small-scale (e.g., <10-ha) areas (Borden 1992, Shea 1994) (note: an effective semiochemical-based tool is not currently available for managing *D. brevicomis*), and applications of insecticides to protect individual trees (Shea et al. 1984, Haverty et al. 1985). Presently, the only effective insecticide technique is to spray the boles of target trees prior to beetle colonization. However, there are concerns regarding the potential for insecticide spray to drift off target. Systemic injections may alleviate some of these concerns, as well as limiting human and other nontarget exposures compared with bole sprays. It should be noted, however, that it is unknown whether senescent needles falling from systemically treated trees contain chemical concentrations that could pose a risk to natural decomposer organisms, as observed with imidacloprid (Kreutzweiser et al. 2008). To our knowledge, this is the first report documenting that a systemic insecticide was successfully used to protect a conifer from bark beetle attack in the western United States. These results are promising, but additional tests are required before we can conclude that emamectin benzoate is an effective preventative treatment for any bark beetle-host system. The temperatures at the Idaho and Utah sites were lower than the 5 to 26°C recorded at the California site. Site conditions such as lower ambient temperatures (e.g., 2 to 16°C [Idaho site] and −1 to 24°C [Utah site] during treatments; Table 1), lower soil temperatures, and lower soil moistures in Idaho and Utah may help explain the lack of efficacy observed, as these factors may slow insecticide uptake and translocation within trees (D. Grosman, personal observations). Future work should include data collection of ambient and soil temperatures, soil type, aspect, and soil moisture at the time of treatment application and during the growing season. The time of year and the number and position of the injection ports could also influence insecticide transport and distribution (Sanchez-Zamora and Fernandez Escobar 2000) and thus efficacy.

Recently, new formulations of emamectin benzoate (TREE-äge) and fipronil have been developed specifically for tree injection. Additional studies are under way to evaluate these new formulations against *D. brevicomis* and *D. ponderosae* (Fettig et al., unpublished data). Future work should evaluate the efficacy of these treatments applied at different times of the year, under different climatic conditions (Sanchez-Zamora and Fernandez Escobar 2000), and against other bark beetle-host tree complexes. In addition, the effects of systemic treatments on nontarget organisms should be assessed (Kreutzweiser et al. 2008). New methodologies have recently been developed that allow determination of emamectin benzoate or fipronil concentrations in pine tissues. These tests should be used to evaluate movement of chemical from the injection sites to different areas of the tree, particularly the phloem region, where bark beetles are exposed as they attack the host.

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