Efficacy of Systemic Insecticides for Protection of Loblolly Pine Against Southern Pine Engraver Beetles (Coleoptera: Curculionidae: Scolytinae) and Wood Borers (Coleoptera: Cerambycidae)

DONALD M. GROSMAN AND WILLIAM W. UPTON

Texas Forest Service, Forest Pest Management, P.O. Box 310, Lufkin, TX 75902–0310

J. Econ. Entomol. 99(1): 94–101 (2006)

ABSTRACT We evaluated the efficacy of the systemic insecticides dinotefuran, emamectin benzoate, fipronil, and imidacloprid for preventing attacks and brood production of southern pine engraver beetles (Coleoptera: Curculionidae: Scolytinae) and wood borers (Coleoptera: Cerambycidae) on standing, stressed trees and bolt sections of loblolly pine, *Pinus taeda* L., in eastern Texas. Emamectin benzoate significantly reduced the colonization success of engraver beetles and associated wood borers in both stressed trees and pine bolt sections. Fipronil was nearly as effective as emamectin benzoate in reducing insect colonization of bolts 3 and 5 mo after injection but only moderately effective 1 mo after injection. Fipronil also significantly reduced bark beetle-caused mortality of stressed trees. Imidacloprid and dinotefuran were ineffective in preventing bark beetle and wood borer colonization of bolts or standing, stressed trees. The injected formulation of emamectin benzoate was found to cause long vertical lesions in the sapwood–phloem interface at each injection point.

KEY WORDS southern pine engraver beetle, systemic insecticide, single-tree protection

THREE SPECIES OF *Ips* engraver beetles (Coleoptera: Curculionidae: Scolytinae) infest pines in the southern United States: the sixspined ips, *Ips calligraphus* (Germar); eastern fivespined ips, *Ips grandicollis* (Eichoff); and small southern pine engraver, *Ips avulsus* (Eichoff). These beetles tend to be secondary pests, normally attacking trees stressed by drought, lightening strikes, root disturbances, and other factors. Local and regional outbreaks of *Ips* spp., often coinciding with regionwide drought, can cause severe pine mortality. For example, losses in 1999 were estimated at $13 million U.S. dollars, second only to southern pine beetle, *Dendroctonus frontalis* Zimmermann, in value lost from insect-caused mortality (reports on losses caused by forest insects, Southern Forest Insect Work Conference 2000). *Ips* engraver beetles do not just affect the timber industry; they also have a significant impact on recreation, water, and wildlife resources as well as residential property. The urban–wildland interface around metropolitan centers is continuing to expand, thus placing more high-valued residential trees at risk to *Ips* attack.

Several species of wood borers also are known to attack and colonize recently dead or felled conifers in this region. They include species in the genera *Monochamus*, *Acanthocinus*, and *Stenocorus* (Coulson and Witter 1984). The females lay eggs on host material, and larvae of these species quickly begin feeding in the phloem before mining into the xylem tissue. The result of this feeding and boring is the quick degredation of wood and its value.

Protection of individual trees from conifer bark beetles has historically involved topical applications of chemical insecticides to the entire bole of the tree by using hydraulic sprayers. Several products had been registered with the Environmental Protection Agency (EPA) for this use, including benzene hexachloride, lindane, fenitrothion (Pestroy), and chlorpyrifos (Dursban), but these insecticides are no longer available for use against bark beetles. Carbaryl is currently registered and is effective against western bark beetle species (Haverty et al. 1998) but ineffective against southern pine bark beetles (Zhong et al. 1994). Permethrin (Astro, Dragnet and Permethrin Pro) and bifenthrin (Onyx) are effective against several species of bark beetles, including *Ips* engraver beetles, but it is not registered for use in forests. Even when available, insecticide spray applications have limitations. They are expensive, time-consuming, present a high risk for worker exposure and drift, and are detrimental to natural enemies (Billings 1980).

Systemic insecticides have been suggested as a potentially useful tool for protection of individual trees or forested areas. One of the first to be tested, acephate (Orthene), was applied to foliage at two different rates (C. E. Crisp, C. E. Richmond, and P. J. Shea, unpublished data in Billings 1980). The treatments were reported to reduce southern pine beetle larval survival, but they had no effect on eggs, pupae, callow, or parent adults. A more recent study evaluated fenitrothion (Pestroy) and a combination treatment of sodium *N*-methyldithiocarbamate (Vapam) plus dimethyl sulfoxide (DMSO) applied to bark hacks and dicrotophos (Bidrin) applied by Mauget injectors (Inject-a-icide-B) to trees at the leading edge of southern pine beetle infestations (Dalusky et al. 1990).

Although none of the treatments prevented tree mortality, dicrotophos significantly reduced both egg gallery length and subsequent brood production. Because dicrotophos has a relatively high mammalian toxicity, it is not available to the general public. Oxdydementon methyl (Metasystox-R) applied by Mauget injectors (Inject-a-cide) is registered for use against several *Dendroctonus* and *Ips* species, but it is not effective against western pine beetle, *Dendroctonus brevicomis* LeConte (Haverty et al. 1996). In addition, according to R. Billings (personal communication), Mauget injectors do not function well on pines because the pressure produced when the injector is primed after installation is often insufficient to overcome the tree's resin pressure.

Emamectin benzoate (Syngenta Crop Protection), an avermectin derivative, has shown systemic activity in pine and is highly effective against pine wood nematode, *Bursaphelenchus xylophilis* (Steiner & Buhrer) Nickle (Takai et al. 2000, 2001, 2003a, b), and coneworm, *Dioryctria* spp. (Grosman et al. 2002), with protection from a single injection lasting >3 yr. Preliminary trials also suggest that this chemical has insecticidal activity against coleopteran pests, including pales weevil, *Hylobius pales* (Herbst) (Jeff Fidgen, unpublished data) and *Anoplophora glabripennis* (Motschulsky) (Poland et al. 2006). Denim 0.15 EC (emamectin benzoate) is registered for use as a foliar spray on cotton against lepidopteran pests. Imidacloprid is a neonicotinoid insecticide with known systemic activity against several coleopteran pests, including Japanese beetle, *Popillia japonica* Newman, and bronze birch borer, *Agrilus anxius* Gory (Dotson 1994). Arborjet, Inc. (Woburn, MA) has recently registered IMA-jet for use in its injection systems for protection of trees against several forest pest species. Fipronil (BASF Corporation), a new pheny pyrazole insecticide shown to have systemic activity in pine, is highly effective in reducing damage from Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock), on young seedlings for >12 mo (D.M.G., unpublished data). Dinotefuran (Valent USA) is another new neonicotinoid with reported activity against chewing and sucking insects. EPA recently designated this active ingredient a reduced risk and organophosphate alternative for ornamentals. Two preliminary trials were conducted in 2004 to evaluate the efficacy of systemic injections of emamectin benzoate, imidacloprid, dinotefuran, and fipronil for reducing success of pine bark beetle attacks on loblolly pine logs and preventing mortality of stressed trees.

Materials and Methods

Two 20-yr-old, recently thinned loblolly pine, *Pinus taeda* L., plantations were selected on land owned by Temple-Inland Forest Products Corporation ≈19 km northwest of Lufkin (Angelina County), TX. Fifteen trees in one plantation were injected with one of four systemic insecticides for use in a bolt (log section) study (trial 1) (31° 27.95′ N, 94° 56.48′ W). Six trees per insecticide were injected in a 0.2-ha section of the second plantation as part of a single-tree protection study (trial 2) (31° 27.67′ N, 94° 56.68′ W). The treatments included the following: 1) Emamectin benzoate (Denim 0.15 EC, 1.92% [AI], Syngenta Crop Protection). Denim was mixed 1:1 with methanol (histological, >99% pure, Fisher, Pittsburgh, PA) and applied at 7.3 ml of solution per centimeter of tree diameter at breast height (dbh) (=0.08 g active per cm dbh); 2) Imidacloprid (IMA-jet, 5% [AI], Arborjet, Inc.). IMA-jet was mixed 1:3 with AAD-jet (Arborjet, Inc.) and applied at 6.3 ml solution per centimeter of tree dbh (=0.08 g active per cm dbh); 3) Fipronil (300 g [AI] per liter emulsifiable concentrate, BASF Corporation). The fipronil formulation was mixed 1:2.8:7.5 with methanol and distilled water and applied at 3.1 ml solution per centimeter of tree dbh (=0.08 g active per cm DBH); 4) Dinotefuran (10% [AI], Valent USA). Dinotefuran was mixed 1:3 with distilled water and applied at 3.1 ml solution per cm of tree dbh (=0.08 g active per cm dbh); and 5) Check (untreated). A staging area also was set up in the second plantation where bolts from the first plantation were exposed to bark beetles and wood borers.

Trial 1. Seventy-five loblolly pine trees, with mean ± SE dbh of 19.0 ± 0.2 cm and height of 16.7 ± 0.2 m, were selected in March 2004. Each treatment consisted of a single insecticide formulation injected into four cardinal points, ≈7 cm in depth and 0.3 m above the ground, on each tree 16–23 April by using the new Arborjet Tree IV microinfusion system (Arborjet, Inc.).

After 1 (24 May), 3 (19 July), and 5 (2 September) mo postinjection, five trees of each treatment were felled, and two 1.5-m-long bolts were removed from the 3- and 8-m heights of the bole. The bolts were transported to a nearby plantation that was recently thinned and contained fresh slash material. Bolts were randomly placed ≈1 m from other bolts on discarded, dry pine bolts to maximize surface area available for colonization as well as to discourage predation by ground and litter-inhabiting organisms. To encourage bark beetle attacks, packets of *Ips* pheromones (racemic ipsdienol [98%, bubble cap] + lanerione [99%, Eppendorf tube] combination, racemic ipsenol [>98%, bubble cap] or *cis*-verbenol [92%, bubble cap]; Phero Tech, Inc., Delta, British Columbia, Canada) were attached separately to three 1-m stakes evenly spaced in the study area. Racemic ipsdienol and *cis*-verbenol were used with the second and third series of bolts deployed in July and September, respectively. The packets were removed after 2 wk when symptoms of bark beetle attacks (boring dust) were observed on most test bolts.

A clear panel of acetate (10 by 25 cm), coated with Stikem Special (Michel and Pelton, Emeryville, CA), was attached to the center of each bolt to monitor arrival of bark beetles for a 2-wk period. The bolts were retrieved ≈3 wk after deployment, after many cerambycid egg niches were observed on the bark surface of most bolts. In the laboratory, two 10- by 50-cm samples (total 1,000 cm^2) of bark were removed from each bolt. The following measurements were recorded from each bark sample: 1) number of unsuccessful *Ips* attacks, i.e., penetration to phloem but no egg galleries; 2) number of successful *Ips* attacks, i.e., construction of nuptial chamber and at least one egg gallery extending from it; 3) number and length of *Ips* egg galleries with larval galleries radiating from them; 4) number and length of *Ips* egg galleries without larval galleries; and 5) percentage of bark sample with cerambycid activity, estimated by overlaying a 100-cm^2 grid on the underside of each bark strip and counting the number of squares where cerambycid larvae had fed.

Treatment efficacy was determined by comparing *Ips* beetle attacks, *Ips* egg gallery number and length, and cerambycid feeding for each treatment. Data were transformed by $\log_{10}(x + 1)$ to satisfy criteria for normality and homoscedasticity (Zar 1984) and analyzed by GLM and the Fisher's protected least significant difference (LSD) test by using the StatView statistical program (SAS Institute, Cary, NC).

At the time of tree felling for the first and second series, a section of lower bole (≈60–80 cm) containing the injection points was taken from each injected tree. The bark was later removed around the injection points to determine whether any damage to tissue had resulted from the installation of plugs and/or injection of chemicals. If damage was found, the length and width of any discolored xylem tissue (lesions) were measured.

Trial 2. Thirty loblolly pines, with mean ± SE dbh of 19.1 ± 0.3 cm and height of 17.4 ± 0.1 m were selected in the second plantation in March 2004 to provide six replicates per treatment. Each treatment was injected into four cardinal points of target trees ≈0.3 m above the ground between 16 and 23 April by using the Arborjet Tree IV system. At 5 wk postinjection (28 May), frills were cut with a hatchet into the sapwood between the injection points near the base of the tree. A cellulose sponge was inserted into each cut and loaded with 10 ml of a 4:1 mix of sodium *N*-methyldithiocarbamate (MS) (Woodfume, Osmose, Inc., Buffalo, NY) plus DMSO (Aldrich, Milwaukee, WI) (Roton 1987, Strom et al. 2004). This treatment reduces resin flow to near zero in 1 to 2 wk. The intent was to stress the trees and make them susceptible to bark beetle attack without directly killing them. Pheromone packets containing racemic ipsdienol + lanerione, ipsenol, or *cis*-verbenol were attached (7 June) atop 3-m stakes evenly spaced in between and around the study trees to encourage attack by the three species of *Ips.* However, the initial results of the bolt trial suggested that encouraging attacks of *Ips calligraphus* (the largest and most common species) alone would allow for easier and more accurate measurements of beetle attack success. Thus, pheromone baits containing only ipsdienol and *cis*-verbenol (pheromones of *I. calligraphus*) were deployed on all stakes on 17 June. The baits were changed every 4 wk throughout the study.

A clear panel of acetate (10 cm × 25 cm) coated with Stickem Special was attached 2 m above ground on standing trees after deployment of pheromone baits to monitor arrival of bark beetles. After 2 wk, the traps were removed and all bark beetles were identified and counted.

Three weeks after pheromone deployment (28 June), each tree was evaluated by marking a 30-cm section of bole at a height of 3 m. All visible *Ips* attacks and cerambycid egg niches were counted within the marked area. The number of trees with fading crowns also was recorded. Thereafter, the trees were evaluated weekly for crown fading. When crown fading did occur, the symptomatic trees were felled, and two bolts taken and evaluated for attack success and gallery length as described in trial 1. All remaining trees were felled on 9 August, 66 d after initial pheromone deployment when no additional trees had died for 3 wk. We feel that this is adequate time because trees often fade with 3 to 4 wk after successful bark beetle attack during the summer (D.M.G., personal observation). Treatment efficacy was determined by comparing tree survival, beetle attacks, and egg gallery number and length on treated and untreated bolts. Data were transformed and statistically analyzed as described for trial 1.

Results

Trial 1. Arborjet's Tree IV system was successfully used to inject all chemical formulations. The installation of the system on each tree (drilling holes, installing plugs, pressurizing the system, and installing needles) usually took ≈5 min when using three systems in tandem. Most injections were completed in just a few minutes.

Evaluation of the phloem and xylem tissue around the injection points at 1 and 3 mo postinjection revealed lesions of various length and widths. Trees injected with dinotefuran or fipronil had lesions that extended a short distance (<6 cm) from the injection points (Table 1). Imidacloprid-induced lesions were nearly twice as long as those induced by the former treatments at 1 mo, but they did not differ from them at 3 mo. Lesions resulting from the emamectin benzoate treatment were significantly longer than those of the other treatments at 1 and 3 mo. In both series of bolts, the actual length of lesions could not be determined because almost all lesions extended beyond the ends of the bolts.

Symptoms of beetle attack (boring dust) were visible on several bolts in just a few days after the bolts had been moved to the staging area and the pheromone baits deployed. Within 2 wk, several *Ips* attacks and numerous cerambycid egg niches were evident on the bark surface of most bolts. There was concern that if cerambycid larvae were allowed to develop for an extended period, their feeding activity would obscure or obliterate the *Ips* galleries. Thus, each series of bolts was retrieved 3 wk after deployment and stored tem-

Table 1. Mean length and width of lesions extending from injection points 1 and 3 mo after injections of four systemic insecticides into loblolly pine (Lufkin, TX)

Treatment	*n*	1 mo postinjection		3 mo postinjection	
		Length (cm)	Width (cm)	Length (cm)	Width (cm)
Dinotephuran	20	3.6 ± 0.6a	1.6 ± 0.1a	5.5 ± 1.0a	1.5 ± 0.1ab
Emamectin benzoate	20	47.3 ± 3.0c[a]	2.3 ± 0.1b	63.5 ± 3.7b[a]	1.8 ± 0.1b
Fipronil	20	4.1 ± 0.6a	1.5 ± 0.1a	4.1 ± 0.5a	1.4 ± 0.1ab
Imidacloprid	20	7.3 ± 0.8b	1.7 ± 0.1a	6.1 ± 0.8a	1.3 ± 0.2a

[a] Lesion usually extended well past the end of the bolt.
Means followed by the same letter in each column are not significantly different at the 5% level based on Fisher's protected LSD.

porarily in a seedling cooler (≈45°F) to slow cerambycid development until the bolts could be evaluated.

Ips *Attack Success.* The number of *Ips* engraver beetles landing on individual bolts varied considerably, but it did not differ among treatments for height or date (Table 2). In contrast, the total number of attacks (nuptial chambers constructed) by male beetles often differed among treatments. The number of attacks (nuptial chambers) was not necessarily reflective of the success of the attack. In May, untreated bolts were heavily attacked. In July, fewer attacks were found on check bolts compared with most of the other treatments. For all three dates, nearly all nuptial chambers were successfully constructed on untreated bolts, with at least one egg gallery radiating from each nuptial chamber. In sharp contrast, on emamectin benzoate-treated bolts evaluated in May, most attacks were unsuccessful (without egg galleries) at the 3 m (79%) and 8 m (69%) heights. By July and September, all (100%) attacks were unsuccessful at both heights. Apparently, all attacks were aborted or the beetles died as they penetrated into the phloem region. There were a few successful *Ips* attacks on one tree out of five in May, but these attacks were significantly fewer compared with those on check trees and were restricted to narrow strips on the bolt. Similarly, in May, a number of trees treated with fipronil and imidacloprid showed patches or strips of reduced attack success. But, the uncolonized strips were usually narrower. This suggests that fipronil and imidacloprid had

Table 2. Trap catches, attack success and gallery construction of *Ips* engravers beetles on loblolly pine bolts cut 1, 3, and 5 mo after trunk injection with four systemic insecticides (Lufkin, TX)

Evaluation period	Bolt ht	Treatment	*Ips* caught/trap	Total no. of nuptial chambers	Nuptial chambers without egg galleries	
					No.	% of total
1 mo postinjection (May)	3 m	Dinotefuran	4.8 ± 1.5a	15.4 ± 3.2a	0.6 ± 0.2a	3.9
		Emamectin	3.8 ± 2.2a	18.6 ± 1.1a	14.6 ± 2.0c	78.5
		Fipronil	4.0 ± 1.1a	21.0 ± 1.7a	10.2 ± 1.4c	48.6
		Imidacloprid	5.6 ± 2.1a	18.2 ± 2.7a	2.0 ± 0.8b	11.0
		Check	6.8 ± 2.0a	16.0 ± 2.5a	0.0 ± 0.0a	0.0
	8 m	Dinotefuran	2.8 ± 0.8a	12.2 ± 2.1a	1.2 ± 0.6ab	9.8
		Emamectin	4.8 ± 1.6a	13.0 ± 8.3ab	9.0 ± 4.3c	69.2
		Fipronil	3.6 ± 1.1a	25.8 ± 2.4bc	2.6 ± 1.4b	10.1
		Imidacloprid	3.8 ± 0.6a	15.8 ± 4.6abc	3.0 ± 0.8bc	19.0
		Check	5.0 ± 1.9a	27.4 ± 0.9c	0.2 ± 0.2a	0.7
3 mo postinjection (July)	3 m	Dinotefuran	5.4 ± 1.9a	5.6 ± 0.6a	1.0 ± 0.4a	17.9
		Emamectin	1.8 ± 0.6a	11.0 ± 4.5ab	11.0 ± 4.5b	100.0
		Fipronil	4.8 ± 2.1a	12.6 ± 1.7b	9.8 ± 1.2b	77.8
		Imidacloprid	2.6 ± 1.2a	10.8 ± 2.7ab	4.2 ± 2.2a	38.9
		Check	2.4 ± 0.2a	6.0 ± 0.9a	0.8 ± 0.8a	13.3
	8 m	Dinotefuran	2.2 ± 0.9a	10.6 ± 2.1bc	1.4 ± 0.4ab	13.2
		Emamectin	3.4 ± 1.7a	8.4 ± 1.8b	8.4 ± 1.8c	100.0
		Fipronil	4.6 ± 1.6a	21.0 ± 4.6c	19.2 ± 5.0c	91.4
		Imidacloprid	2.0 ± 1.8a	9.4 ± 2.2b	3.8 ± 1.7b	40.4
		Check	2.8 ± 1.6a	3.8 ± 1.4a	0.0 ± 0.0a	0.0
5 mo postinjection (Sept.)	3 m	Dinotefuran	2.6 ± 1.3a	4.2 ± 0.9ab	0.0 ± 0.0a	0.0
		Emamectin	1.2 ± 1.0a	3.8 ± 1.3a	3.8 ± 1.3b	100.0
		Fipronil	1.2 ± 0.6a	8.0 ± 2.0b	7.4 ± 2.0c	92.5
		Imidacloprid	1.6 ± 0.5a	4.6 ± 0.9ab	0.2 ± 0.2a	4.3
		Check	1.6 ± 0.7a	5.2 ± 1.0ab	0.0 ± 0.0a	0.0
	8 m	Dinotefuran	0.6 ± 0.6a	5.2 ± 0.4a	0.2 ± 0.2a	3.8
		Emamectin	0.4 ± 0.2a	4.4 ± 1.5a	4.4 ± 1.5b	100.0
		Fipronil	0.8 ± 0.4a	6.6 ± 2.3a	5.4 ± 1.7b	81.8
		Imidacloprid	1.5 ± 0.5ab	7.2 ± 1.7a	2.2 ± 0.7b	30.6
		Check	2.2 ± 0.6b	7.8 ± 1.6a	0.0 ± 0.0a	0.0

Means followed by the same letter in each column within date and height are not significantly different at the 5% level based on Fisher's protected LSD.

Table 3. Mean number and length of egg galleries constructed by *Ips* engravers beetles in loblolly pine bolts cut 1, 3, and 5 mo after trunk injection with four systemic insecticides (Lufkin, TX)

Evaluation period	Bolt ht.	Treatment	No. of egg galleries: Total no.	No. of egg galleries without larvae: No.	No. of egg galleries without larvae: % of total	Length of egg galleries: Total length	Length of egg galleries without larvae: cm	Length of egg galleries without larvae: % of Total	Cerambycid feeding area
1 mo postinjection (May)	3 m	Dinotefuran	54.0 ± 11.3b	33.2 ± 9.7b	61.5	329.4 ± 39.6bc	146.0 ± 45.3b	44.3	28.3 ± 6.9c
		Emamectin	12.4 ± 6.1a	10.0 ± 5.9a	80.6	30.7 ± 18.3a	15.5 ± 6.2a	50.5	2.2 ± 1.8a
		Fipronil	33.6 ± 9.3b	23.6 ± 6.5b	70.2	135.0 ± 46.8b	64.4 ± 20.6b	47.7	5.4 ± 1.5ab
		Imidacloprid	65.2 ± 4.8b	35.2 ± 6.0b	54.0	442.2 ± 24.9c	159.0 ± 29.4b	36.0	11.8 ± 3.3bc
		Check	65.8 ± 8.2b	29.0 ± 4.7b	44.1	483.2 ± 113.7c	114.8 ± 33.7b	23.8	29.9 ± 6.1c
	8 m	Dinotefuran	42.4 ± 4.1b	29.2 ± 3.2b	68.9	231.2 ± 40.4b	128.0 ± 32.6b	55.4	13.6 ± 5.0b
		Emamectin	4.2 ± 4.0a	4.0 ± 3.8a	95.2	13.5 ± 12.9a	12.3 ± 11.7a	91.1	0.0 ± 0.0a
		Fipronil	73.0 ± 2.8b	46.2 ± 2.7b	63.3	332.8 ± 35.4b	149.6 ± 21.9b	45.0	15.4 ± 4.5b
		Imidacloprid	49.0 ± 12.0b	29.6 ± 9.6b	60.4	315.8 ± 51.5b	118.8 ± 33.7b	37.6	0.6 ± 0.4a
		Check	94.6 ± 7.4b	30.0 ± 6.9b	31.7	588.2 ± 37.2b	104.4 ± 25.0b	17.7	34.1 ± 1.5c
3 mo postinjection (May)	3 m	Dinotefuran	17.0 ± 1.8c	3.4 ± 1.9ab	20.0	162.8 ± 9.8c	12.4 ± 7.3ab	7.6	33.1 ± 3.2c
		Emamectin	0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a
		Fipronil	5.6 ± 2.8b	5.6 ± 2.8b	100.0	19.4 ± 8.4b	19.4 ± 8.4b	100.0	1.5 ± 1.5a
		Imidacloprid	20.6 ± 5.8c	6.4 ± 3.3b	31.3	187.4 ± 38.5c	36.0 ± 20.8b	19.2	14.0 ± 4.8b
		Check	17.0 ± 1.2c	2.2 ± 0.8ab	12.9	156.4 ± 19.9c	14.4 ± 6.5b	9.2	23.0 ± 4.1bc
	8 m	Dinotefuran	27.6 ± 8.5c	10.4 ± 5.7c	37.7	212.0 ± 45.8c	59.8 ± 26.5c	28.2	33.9 ± 10.3b
		Emamectin	0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a
		Fipronil	3.0 ± 0.9b	2.8 ± 1.0bc	93.3	9.2 ± 3.6b	8.2 ± 3.5b	89.1	0.0 ± 0.0a
		Imidacloprid	17.4 ± 6.1c	8.2 ± 2.8c	47.1	130.0 ± 47.1c	42.6 ± 12.3bc	32.8	8.3 ± 5.3b
		Check	13.0 ± 2.8c	1.0 ± 0.6ab	7.7	156.0 ± 25.9c	2.4 ± 1.6ab	1.5	24.5 ± 11.9b
5 mo postinjection (Sept.)	3 m	Dinotefuran	12.0 ± 2.9e	2.6 ± 1.1bc	21.7	114.4 ± 27.6c	12.8 ± 4.8c	11.2	16.9 ± 5.3c
		Emanectin	0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a
		Fipronil	1.0 ± 0.4b	0.6 ± 0.4ab	60.0	5.8 ± 3.1b	2.4 ± 1.5ab	41.4	1.7 ± 1.6ab
		Imidacloprid	13.2 ± 2.6c	1.4 ± 0.6abc	10.6	163.4 ± 35.1c	9.2 ± 5.6bc	5.6	5.9 ± 2.7bc
		Check	15.8 ± 2.6c	2.8 ± 0.7c	17.7	160.4 ± 31.3c	9.8 ± 2.7c	6.1	9.3 ± 3.9c
	8 m	Dinotefuran	19.8 ± 1.9c	7.8 ± 2.2d	39.4	184.6 ± 13.8c	57.8 ± 16.2c	31.3	3.6 ± 1.9b
		Emamectin	0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a
		Fipronil	2.0 ± 1.4b	0.8 ± 0.6ab	40.0	15.2 ± 13.7b	2.2 ± 1.4a	14.5	0.0 ± 0.0a
		Imidacloprid	18.0 ± 3.2c	3.4 ± 1.7c	18.9	164.4 ± 25.1c	19.6 ± 8.5b	11.9	4.5 ± 1.9b
		Check	20.2 ± 1.5c	2.4 ± 0.6bc	11.9	234.2 ± 28.9c	10.8 ± 6.3b	4.6	14.2 ± 6.5b

Means followed by the same letter in each column within date and height are not significantly different at the 5% level based on Fisher's protected LSD.

not dispersed to the same extent as did emamectin benzoate. Nearly half (49%) of the attacks on fipronil-treated trees were unsuccessful (without egg galleries) on bolts taken from 3 m. This treatment only slightly reduced attack success (10%) at the 8-m height. Both treatments, fipronil in particular, were more effective by July in preventing successful attacks on 3- (78%) and 8-m (91%) bolts. The clear, uncolonized area extended nearly all the way around the fipronil-treated tree boles, whereas the clean areas were still narrow or nonexistent on imidacloprid bolts.

In May, emamectin benzoate significantly reduced the total number (81 and 96%) and length (94 and 99%) of egg galleries at 3 and 8 m, respectively, compared with check trees (Table 3). No other treatment reduced the total number of galleries. However, when the number and length of galleries with brood were compared with galleries without brood, all injection treatments reduced the proportion of galleries with brood and their lengths relative to the checks. Fipronil was second only to emamectin benzoate in reducing the number and length of egg galleries with brood. In July and September, emamectin benzoate completely prevented the construction of egg galleries in all bolts. Fipronil was nearly equal in its efficacy in July and September. Although a few egg galleries were constructed, almost none had developing brood. Imidacloprid and dinotefuran did reduce the proportion of galleries with brood and their lengths relative to the checks, but the proportions were all >50% of the totals.

Cerambycid Larval Feeding. In May, cerambycid larvae had fed upon 30 and 34% of the phloem area on untreated bolts taken from 3 and 8 m, respectively, during the 3-wk period between tree felling and bolt evaluation (Table 3). In contrast, significantly less larval feeding occurred on emamectin benzoate-treated bolts. Overall, this treatment reduced feeding

Table 4. Trap catches and attacks of *Ips* engravers beetles and cerambycids (egg niches) on standing loblolly pine after trunk injection with four systemic insecticides (Lufkin, TX)

Treatment	Mean no. of *Ips* caught/trap	Mean no. of attacks/0.3-m bole section at 3 m after 24 d: *Ips*	Mean no. of attacks/0.3-m bole section at 3 m after 24 d: Cerambycid
Dinotefuran	8.7b	6.2 ± 1.7b	4.5 ± 1.8a
Emamectin	1.2a	0.5 ± 0.2a	0.8 ± 0.3a
Fipronil	5.2ab	1.3 ± 1.0a	1.3 ± 0.7a
Imidacloprid	8.5b	12.7 ± 1.7c	4.7 ± 1.7a
Check	6.5b	14.7 ± 1.6c	4.3 ± 1.9a

Means followed by the same letter in each column are not significantly different at the 5% level based on Fisher's protected LSD.

Table 5. Visible signs of mortality of standing loblolly pine after trunk injection with four systemic insecticides (Lufkin, TX)

Treatment	% of trees[a] with fading crowns after					
	24 d	32 d	39 d	46 d	52 d	66 d
Dinotefuran	16.7ab	66.7b	83.3b	83.3b	83.3b	83.3b
Emamectin	0.0a	0.0a	0.0a	0.0a	0.0a	0.0a
Fipronil	0.0a	0.0a	0.0a	0.0a	0.0a	0.0a
Imidacloprid	50.0b	83.3b	83.3b	83.3b	100.0b	100.0b
Check	33.3ab	66.7b	83.3b	83.3b	83.3b	83.3b

Means followed by the same letter in each column are not significantly different at the 5% level based on Fisher's protected LSD.
[a] $n = 6$, number of trees represented by this percentage.

damage by 93 and 100% on bolts from 3 and 8 m, respectively. Fipronil reduced feeding by 82% on bolts at 3 m but only by 55% at 8 m. Imidacloprid reduced feeding by 98% on bolts at 8 m but only by 61% at 3 m. Dinotefuran showed a similar trend, having no apparent effect at 3 m but reducing feeding by 60% at 8 m. Cerambycid larvae feeding area in untreated bolts decreased in July (23–25%) and September (9–14%) (Table 3). In contrast, no larval feeding was observed on emamectin benzoate-treated bolts from 3 m, and larval feeding was evident on only 2% of the fipronil bolts from the same height. No colonization occurred at 8 m for either treatment. Imidacloprid and dinotefuran had no significant effect on the extent of cerambycid larval feeding 3 or 5 mo after injection.

Trial 2. The Vapam/DMSO treatment had the desired effect of stressing the trees and predisposing them to *Ips* attack. Resin weeping down the bark surface, the most visible sign of stress, occurred on nearly 40% of study trees. The proportion of trees with this stress symptom did not differ significantly among treatments ($F = 0.4487$; df = 4, 25; $P = 0.7723$). Five of the six check trees showed signs of bark beetle attack (pitch tubes and boring dust) 2 wk after the Vapam/DMSO treatment was applied.

Approximately 4 wk after the Vapam/DMSO treatment (=24 d after initial pheromone deployment), all checks and imidacloprid-treated trees were heavily attacked by *Ips*, and most had two or more cerambycid egg niches at 3 m (Table 4). In contrast, emamectin benzoate- and fipronil-treated trees had significantly fewer *Ips* attacks at the same height. Of the few *Ips* attacks that were found on these trees, nearly all seemed to have been unsuccessful (pitch tubes at the entrance holes were dry and brittle). There were no significant differences in the number of cerambycid egg niches among the treatments, but there were differences in the proportion of trees with fading crowns (Table 5). None of the emamectin benzoate- and fipronil-treated trees had fading crowns, whereas one-half (three of six) of the imidacloprid-treated trees faded. Two check trees and one dinotefuran-treated tree also exhibited fading crowns.

The study was discontinued after 66 d when no additional trees had faded in 20 d (Table 5). At the end of the experiment, all of the imidacloprid-treated and five of six (83%) of each of the check and dinotefuran-treated trees had died because of bark beetle attack. In contrast, all emamectin benzoate- and fipronil-treated trees survived. Evaluation of cut bolts showed that all trees had been attacked, but the emamectin benzoate-treated bolts had significantly fewer attacks than the check (Table 6). Attacks that did occur were unsuccessful. One fipronil tree was partially colonized and may have ultimately succumbed to attack if the trial had been extended a few more weeks. Assuming eventual death of this tree, 83% of the fipronil-treated trees remained alive, indicating that fipronil would be a good protection option. Both emamectin benzoate- and fipronil-treated bolts had significantly fewer and shorter *Ips* egg galleries with and without brood and less area fed upon by cerambycid larvae compared with all other treatments (Table 7).

Conclusions. All chemical formulations were quickly injected into the study trees for both trials by using the Arborjet Tree IV system. However, evaluation of the phloem and xylem surrounding the injection points revealed that the emamectin benzoate solution caused the development of long vertical lesions. The occurrence of these lesions indicates that at least one component of the injected formulation is detrimental to plant tissue. Because methanol was used as a solvent in both the emamectin benzoate and fipronil formulations, it is unlikely that this component caused the lesions. Denim (emamectin benzoate) was developed for spray applications to crops and contains three inert ingredients (mineral oil, butylated hy-

Table 6. Effects of four systemic insecticides on attack success and gallery construction of *Ips* engraver beetles on loblolly pine bolts cut after tree mortality or the end of the trial (Lufkin, TX)

Bolt ht	Treatment	Total no. of nuptial chambers	Nuptial chambers without egg galleries	
			No.	% total
3 m	Dinotefuran	17.7 ± 2.9c	6.8 ± 1.4b	38.7
	Emamectin	3.0 ± 1.5a	3.0 ± 1.5ab	100.0
	Fipronil	6.2 ± 2.2ab	5.0 ± 1.7b	81.1
	Imidacloprid	8.2 ± 1.1bc	0.2 ± 0.2a	2.0
	Check	9.7 ± 2.5bc	3.2 ± 1.7ab	32.8
8 m	Dinotefuran	4.2 ± 0.9ab	0.3 ± 0.2a	8.0
	Emamectin	1.3 ± 0.8a	1.3 ± 0.8ab	100.0
	Fipronil	4.5 ± 2.7ab	1.5 ± 1.0ab	33.3
	Imidacloprid	12.5 ± 2.9b	2.7 ± 1.0b	21.3
	Check	6.8 ± 2.1b	0.8 ± 0.4ab	12.2

Means followed by the same letter in each column within height are not significantly different at the 5% level based on Fisher's protected LSD.

Table 7. Effects of four systemic insecticides on gallery construction of *Ips* engravers beetles and cerambycid larval feeding in loblolly pine bolts cut after tree mortality or at the end of the trial (Lufkin, TX)

Bolt ht	Treatment	No. of egg galleries			Length of egg galleries			Cerambycid feeding area
		Total no.	without larvae		Total length	without larvae		
			No.	% of total		cm	% of total	
3 m	Dinotefuran	30.0 ± 8.4b	18.3 ± 5.3b*	61.1	157.5 ± 36.4b	71.2 ± 21.4b	45.2	9.8 ± 5.0b
	Emamectin	0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a
	Fipronil	1.2 ± 0.5a	1.0 ± 0.5a	85.7	6.0 ± 3.7a	3.5 ± 1.6a	58.3	0.0 ± 0.0a
	Imidacloprid	38.2 ± 5.1b	27.2 ± 4.4b	71.2	301.5 ± 45.1b	179.8 ± 43.7c	59.6	5.7 ± 3.6b
	Check	28.8 ± 5.7b	17.2 ± 5.5b	59.5	225.5 ± 66.7b	108.3 ± 57.7bc	48.0	3.6 ± 1.4b
8 m	Dinotefuran	26.8 ± 6.1b	11.3 ± 3.6bc	42.2	230.2 ± 54.4b	83.7 ± 28.3b	36.4	11.7 ± 4.6c
	Emamectin	0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a	0.0 ± 0.0a		0.0 ± 0.0a
	Fipronil	7.7 ± 11.9a	7.2 ± 4.6ab	93.5	22.7 ± 14.6a	20.2 ± 13.6a	89.0	0.0 ± 0.0a
	Imidacloprid	33.2 ± 15.0b	19.0 ± 5.5c	57.3	217.5 ± 33.9b	102.0 ± 33.5b	46.9	0.5 ± 0.5ab
	Check	45.7 ± 14.0b	18.5 ± 5.9c	40.5	295.0 ± 72.4b	91.0 ± 24.6b	30.8	6.2 ± 2.9bc

Means followed by the same letter in each column within height are not significantly different at the 5% level based on Fisher's protected LSD.

droxytolulene, and an organic solvent) (Denim MSDS) that allow the active ingredient to spread and adhere to the foliar surface. A recent subtractive bioassay conducted by Arborjet, Inc. with white pine, *Pinus strobus* L., suggests that the organic solvent component in the Denim formulation caused the excessively long lesions on emamectin benzoate-treated trees (Joe Doccola, personal communication). Further tests are needed to develop an emamectin benzoate formulation for injection that is effective against target insects, yet nontoxic to the trees.

In both trials, emamectin benzoate was highly effective in preventing successful attacks by *Ips* bark beetles and cerambycids 1, 3, and 5 mo after injection. On the bolts, at least, those male *Ips* that initiated attacks were either deterred or killed upon penetration into the phloem layer and exposure to the active ingredient. It is surmised that any pheromone production by males as they burrowed through the bark was halted prematurely. Without these pheromones, very few, if any, females were attracted to the host material or entered the nuptial chamber to mate and begin construction of egg galleries. Even when females did arrive on a few of the logs of the first series and began construction of galleries, the galleries were very short and brood did not develop beyond the initial instars. Assuming that this scenario also occurred in the standing trees, the halting of pheromone production upon male contact with the phloem layer also halted the attraction of additional males, thereby preventing the mass attack of the host tree as indicated by fewer numbers of *Ips* caught per trap (Table 4).

Fipronil also showed good activity against bark beetles and cerambycids in the bolt trial. However, the diffusion of fipronil throughout the tree seemed to be slower than that of emamectin benzoate and thus was incomplete 4 wk after injection as indicated by the strips of clean, uncolonized phloem. With additional time (≥3 months), the chemical had dispersed enough in the tree to provide full protection from beetle attack.

Imidacloprid and dinotefuran, both neonicotinoid compounds, did not seem to have any marked effect against bark beetles. Imidacloprid effectively reduced the amount of cerambycid larval feeding 1 mo postinjection, but it was only marginally effective after 3 mo in both the bolt and standing tree trials and did not differ from the check after 5 mo. These findings support the reported activity by imidacloprid against *A. glabripennis*, another cerambycid (Poland et al. 2006; Joe Doccola, personal communication), but also suggest that emamectin benzoate and fipronil may provide better, longer term tree protection against this exotic pest species.

Although the above-mentioned small trials were established to gather preliminary data on the efficacy of four potential systemic insecticides, the results indicate that two chemicals, emamectin benzoate and fipronil, consistently and significantly reduced the colonization success of both *Ips* engraver beetles and wood borers. We recognize the need to conduct addition trials to confirm the effectiveness of emamectin benzoate and fipronil against other species of destructive bark beetles and wood borers.

It is conceivable that single injections of these chemicals also may protect trees against bark beetles and wood borers for >1 yr, as documented for emamectin benzoate and fipronil used against other forest and seed orchard pests (Grosman et al. 2002; Takai et al. 2003a, b). Duration trials using these chemicals for prevention of attacks by *Dendroctonus* or *Ips* bark beetles are needed to validate this hypothesis.

Acknowledgments

We thank Jamie Burns, Valena Bryan, Brian Pope, Billy Whitworth, Dustin Hollowell, and Libor Myslevic for field and laboratory assistance and companies named herein for donating injection systems and insecticides. We also thank Temple-Inland Forest Product Corp. and Emily Goodwin who provided the study sites. Brian Strom (U.S. Forest Service–FHP) donated the Vapam. Ronald Billings and Herbert Pase (Texas Forest Service), Dave Cox (Syngenta Crop Protection), and Harold Quicke (BASF Corporation) provided helpful comments and insight on an earlier version of this manuscript. This research was supported by the Western Gulf Forest Pest Management Cooperative.

References Cited

Billings, R. F. 1980. Direct control, pp. 179–192. *In* R. C. Thatcher, J. L. Searcy, J. E. Coster, and G. O. Hertel [eds.], The southern pine beetle. U.S. Dep. Agric. Tech. Bull. 1631.

Coulson, R. N., and J. A. Witter. 1984. Forest Entomology Ecology and Management. John Wiley and Sons, New York.

Dalusky, M. J., C. W. Berisford, and P. B. Bush. 1990. Efficacy of three injected chemical systems for control of the southern pine beetle. Ga. For. Commun. Ga. For. Res. Paper 83.

Dotson, J. A. 1994. Merit product information manual. Bayer Corp., Kansas City, MO.

Grosman, D. M., W. W. Upton, F. A. McCook, and R. F. Billings. 2002. Systemic insecticide injections for control of cone and seed insects in loblolly pine seed orchards –2 year results. South. J. Appl. For. 26: 146–152.

Haverty, M. I., P. J. Shea, and J. M. Wenz. 1996. Metasystox-R, applied in Mauget injectors, ineffective in protecting individual ponderosa pines from western pine beetles. U. S. Dep. Agric.–Forest Service Pacific Southwest Research Station Research Note 420.

Haverty, M. I., P. J. Shea, J. T. Hoffman, J. M. Wenz, and K. E. Gibson. 1998. Effectiveness of esfenvalerate, cyfluthrin, and carbaryl in protecting individual lodgepole pines and ponderosa pines from attack by *Dendroctonus* spp. U. S. Dep. Agric.–Forest Service Pacific Southwest Research Station Research Paper 237.

Poland, T. M., R. A. Haack, T. R. Petrice, D. L. Miller, L. S. Bauer, and R. Gao. 2006. Field evaluations of systemic insecticides for control of the Asian longhorned beetle, *Anoplophora glabripennis* (Coleoptera: Cerambycidae), in China. J. Econ. Entomol. (in press).

Roton, L. M. 1987. Promising treatment for southern pine beetles. Am. Papermaker 50: 30–32.

Strom, B. L., S. R. Clarke, and P. J. Shea. 2004. Efficacy of 4-allyanisole-based products for protecting individual loblolly pines from *Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae). Can. J. For. Res. 34: 659–665.

Takai, K., T. Soejima, T. Suzuki, and K. Kawazu. 2000. Emamectin benzoate as a candidate for a trunk-injection agent against the pine wood nematode, *Bursaphelenchus xylophilus.* Pest Manag. Sci. 56: 937–941.

Takai, K., T. Soejima, T. Suzuki, and K. Kawazu. 2001. Development of a water-soluble preparation of emamectin benzoate and its preventative effect against the wilting of pot-grown pine trees inoculated with the pine wood nematode, *Bursaphelenchus xylophilus.* Pest Manag. Sci. 57: 463–466.

Takai, K., T. Suzuki, and K. Kawazu. 2003a. Development and preventative effect against pine wilt disease of a novel liquid formulation of emamectin benzoate. Pest Manag. Sci. 59: 365–370.

Takai, K., T. Suzuki, and K. Kawazu. 2003b. Distribution and persistence of emamectin benzoate at efficacious concentrations in pine tissues after injection of a liquid formulation. Pest Manag. Sci. 60: 42–48.

Zar, J. H. 1984. Biostatistical analysis. Prentice Hall, Englewood Cliffs, NJ.

Zhong, H., F. L. Hastings, F. P. Hain, and R. A. Werner. 1994. Toxicity of carbaryl toward the southern pine beetle in filter paper, bark and cut bolt bioassays. J. Entomol. Sci. 29: 247–253.

Received 15 June 2005; accepted 4 November 2005.